

Antiprotons and Elementary Particles over a Solar Cycle: Results from the Alpha Magnetic Spectrometer

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We present results over an 11-year Solar cycle of cosmic antiprotons based on 1.1×10^6 events in the rigidity range from 1.00 to 41.9 GV. The \bar{p} fluxes exhibit distinct properties. The magnitude of the \bar{p} flux temporal variation is significantly smaller than those of p , e^- , and e^+ . A hysteresis between the \bar{p} fluxes and the p fluxes is observed, whereas the \bar{p} and e^- fluxes show a linear correlation. With a model-independent analysis, we found a universal relation between the shape of the rigidity spectrum and the magnitude of flux temporal variation over an 11-year Solar cycle for both positively and negatively charged particles. The simultaneous results on \bar{p} and p , e^- , and e^+ provide unique information for understanding particle transport in the Solar System as a function of mass, charge, and spectral shape.

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In this Letter, we present continuous antiproton \bar{p} flux measurements per Bartels rotation (BR: 27 days) across an 11-year period from May 2011 to June 2022 in the rigidity range from 1.00 to 41.9 GV, based on 1.1×10^6 antiprotons collected by the Alpha Magnetic Spectrometer (AMS) on the International Space Station (ISS). Together with the AMS results on protons p , electrons e^- , and positrons e^+ , these measurements of the time and rigidity dependence of charged elementary particles provide unique inputs for a comprehensive study of effects related to the solar magnetic field [1].

The knowledge of the fluxes of charged elementary particles is crucial in understanding phenomena in the cosmos [2–4], such as the nature of dark matter. Experimental data on \bar{p} are limited due to the low rate and overwhelming background; for each antiproton, there are approximately 10^4 protons. Since the first observation of antiprotons in cosmic rays [5], many studies on the antiproton flux and antiproton-to-proton flux ratio have been performed at different times and time intervals [6–13]. The AMS measurements of the cosmic antiproton flux [14,15] have generated widespread discussions about their origins [16].

The fluxes of charged cosmic rays outside the heliosphere are thought to be stable on the timescale of decades [17–21]. Time-dependent variations in galactic cosmic-ray fluxes measured inside the heliosphere are expected only due to solar modulation [1]. Solar modulation involves convective, diffusive, particle drift, and adiabatic energy loss processes [22,23]. The modulation effect depends on the rigidity, charge sign, mass, and shape of the rigidity spectra outside the heliosphere [24–31]. In the force-field approximation and many other models [22–33], the modulation effect from the spectral shape originates from the energy losses of particles in the heliosphere. At a given rigidity, this process decreases the overall modulation effect if the flux is increasing with rigidity and increases the overall modulation effect if the flux is decreasing with rigidity [32,33].

Previously, AMS has reported short-term variations on the scale of days to months and long-term variations on the scale of years in the daily fluxes of protons [34], electrons [35], and positrons [36]. Antiprotons have an identical mass but the opposite charge sign as protons and a different mass but the same charge sign as electrons. In addition, the \bar{p} flux has a unique spectral shape at low rigidity [6–15]. This information provides a distinct channel for understanding solar modulation effects [37–47]. Moreover, accurate knowledge of the solar modulation effects on antiproton fluxes is crucial for understanding the origin of antiprotons in the cosmos [7,48].

The data presented in this Letter cover the main portion of Solar cycle 24, including the polarity reversal of the solar magnetic field in 2013 [49], and the beginning of Solar cycle 25. The simultaneous measurement of all four elementary particles provides comprehensive information for understanding solar modulation.

Detector—The layout and description of the AMS detector are presented in Refs. [15,50] and shown in Fig. S1 in Supplemental Material [51]. The key elements used in this measurement are the permanent magnet [52], the silicon tracker [53–55], the transition radiation detector (TRD) [56], the four planes of time of flight (TOF) scintillation counters [57], the ring imaging Čerenkov detector (RICH) [58], and the electromagnetic calorimeter (ECAL) [59,60]. More information on AMS layout, performance, trigger, and Monte Carlo simulation [61] is detailed in Supplemental Material [51].

Event selection—Over 2.0×10^{11} cosmic-ray events have been recorded in the first 11 years of AMS operations. In the rigidity range from 1.00 to 41.9 GV, we select antiproton samples using the combined information of TRD, TOF, RICH, silicon tracker, and ECAL. The details of the event selection, including the geomagnetic cutoff [62,63] and the backgrounds, are contained in Supplemental Material [51] and in Refs. [14,15]. After selection and background subtraction, we obtained 1.1×10^6 antiprotons.

Data analysis—The isotropic flux in the i th absolute rigidity bin ($R_i, R_i + \Delta R_i$) for the j th time period is given by

$$\Phi_i^j = \frac{N_i^j}{A_i^j(1 + \delta_i^j)\epsilon_i^j T_i^j \Delta R_i}, \quad (1)$$

where N_i^j is the number of events corrected for background and bin-to-bin migration using the unfolding procedure described in Ref. [64], A_i^j is the effective acceptance determined from the Monte Carlo simulation including geometric acceptance, event selection efficiencies, and interactions of antiprotons in the AMS materials, δ_i^j is the small correction to the acceptance due to the difference in selection efficiencies between data and Monte Carlo simulation, ϵ_i^j is the trigger efficiency, and T_i^j is the collection time (see Supplemental Material [51] for details). The antiproton flux for each Bartels rotation period is measured in 139 Bartels rotations from May 2011 to June 2022 in 11 rigidity bins from 1.00 to 41.9 GV.

The small corrections δ_i^j are estimated by comparing the efficiencies in data and Monte Carlo simulation of every selection cut using information from the detectors unrelated to that cut [14]. The δ_i^j are found to have a small rigidity dependence, smoothly varying from 8% at 1 GV to 3% at 10 GV.

Extensive studies of both time-dependent and time-independent systematic errors were performed. The major sources of systematic errors include the uncertainties in the background subtraction, the trigger efficiency, the geomagnetic cutoff, the acceptance calculation, the unfolding, and the absolute rigidity scale.

The uncertainty in background subtraction comprises two components: event selection and statistical fluctuation of the background template used to differentiate antiprotons from electrons and pions [14]. The systematic error due to event selection is 3.5% at 1 GV and 0.5% at 10 GV. The statistical fluctuation of the template affects the antiproton signal yield. This uncertainty is estimated by sampling the template according to the statistics and repeating the fitting, as well as by varying the fitting procedure. This error is 1.5% at 1 GV and less than 1% above 3 GV. These two components are independent and are added in quadrature.

The systematic error on antiproton fluxes associated with the trigger efficiency measurement is $< 1\%$ over the entire rigidity range and for every Bartels rotation.

The geomagnetic cutoff is calculated as described in Supplemental Material [51], and the resulting systematic error on the fluxes is about 2% at 1 GV and negligible (less than 0.4%) above 2 GV.

The systematic error of the effective acceptance is primarily due to the uncertainty in the interaction cross sections for antiprotons with the detector materials. It is independent of time and is 4% at 1 GV, decreasing smoothly to 2% above 20 GV [14]. The systematic error of the acceptance correction associated with the efficiency of selection and reconstruction is below 1%.

The systematic error associated with unfolding includes time-dependent and time-independent errors. The time-independent error comes from the uncertainty of the rigidity resolution function which has a pronounced Gaussian core and non-Gaussian tails. This error is obtained by repeating the unfolding procedure while independently varying the width of the Gaussian core by 5% and non-Gaussian tails by 20%. The resulting systematic error in the flux is 2.5% at 1 GV and decreases to less than 0.2% above 10 GV. The additional time-dependent systematic error in the unfolding procedure due to the variation of the antiproton spectral shape per Bartels rotation is about 4% at 1 GV and negligible (less than 0.3%) above 3 GV for all Bartels rotations.

The systematic error associated with the absolute rigidity scale has two sources. The first is due to residual tracker misalignment, and the second comes from the magnetic field map measurement with its temperature corrections [34]. The total time-independent systematic error on the fluxes due to uncertainty on the rigidity scale is less than 0.5% up to 41.9 GV.

The total systematic error is obtained by adding in quadrature the individual contributions of the time-independent systematic errors and the time-dependent systematic errors discussed above. For all Bartels rotations, at 1 GV it is about 9%, and above 5 GV it is about 4%.

Most importantly, several independent analyses were performed on the same data sample by different study groups. The results of those analyses are consistent with this Letter.

Results—The antiproton fluxes for each Bartels rotation, $\Phi_{\bar{p}}^{\text{BR}}$, including statistical errors, time-dependent systematic errors, and total systematic errors are tabulated in Tables S1–S139 in Supplemental Material [51] as functions of rigidity at the top of the AMS detector. The time-averaged antiproton flux $\langle\Phi_{\bar{p}}\rangle$ over the 11-year Solar cycle is tabulated in Table S140 in Supplemental Material [51]. The tables are also provided in a machine-readable form [65]. The proton fluxes Φ_p , the electron fluxes Φ_{e^-} , and the positron fluxes Φ_{e^+} are taken from Refs. [34–36]. They are rebinned in order to compare with the antiproton data. The complete rebinned Φ_p , Φ_{e^-} , and Φ_{e^+} data up to June 2022 are provided in a machine-readable form [34–36].

Figure 1 presents the antiproton fluxes as a function of rigidity and as a function of time. The fluxes measured for each Bartels rotation ($\Phi_{\bar{p}}^{\text{BR}}$) are presented in Fig. 1(a) below 2.97 GV, where the fluxes increase with increasing rigidity, and above 2.97 GV in Fig. 1(b), where the fluxes decrease with increasing rigidity. To examine the 11-year variations of the antiproton fluxes, Figs. 1(c) and 1(d) present the $\Phi_{\bar{p}}$ using their 13-BR moving average with a step of 1 BR for the same rigidities as in Figs. 1(a) and 1(b), respectively. As seen, $\Phi_{\bar{p}}$ exhibit distinct properties as a function of time. Below ~ 10 GV, $\Phi_{\bar{p}}$ exhibit significant temporal variation and the relative magnitudes of the flux variations decrease with increasing rigidity. Figures 1(e) and 1(f) present the three-dimensional variation of $\Phi_{\bar{p}}$ as functions of time and rigidity. Figure S2 in Supplemental Material [51] shows $\langle\Phi_{\bar{p}}\rangle$ together with other measurements collected over much shorter time intervals [6–13]. As seen, $\langle\Phi_{\bar{p}}\rangle$ exhibits distinct properties as a function of rigidity: From 1 to 2 GV the flux increases with rigidity, from 2 to 4 GV the flux reaches a maximum and turns over at ≈ 3 GV, and from 4 GV the flux continues to decrease.

Figure 2 presents the fluxes of elementary particles measured by AMS in the 11-year period. Figure 2(a) shows the time-averaged fluxes $\langle\Phi_p\rangle$, $\langle\Phi_{e^-}\rangle$, $\langle\Phi_{e^+}\rangle$, and $\langle\Phi_{\bar{p}}\rangle$ as a function of rigidity. As seen, the rigidity dependence of $\langle\Phi_{\bar{p}}\rangle$ is distinctly different from that of the other fluxes which all decrease with increasing rigidity. The ranges of flux temporal variation during this period are presented as shaded bands. Figure S3 in Supplemental Material [51] presents the temporal evolution of all elementary particle fluxes for four characteristic rigidity bins using their 13-BR moving average values. As seen, below ≈ 4 GV, the magnitude of the $\Phi_{\bar{p}}$ temporal variation is significantly smaller compared to that of the other fluxes. All four fluxes reach a minimum around 2014–2015 and a maximum around 2020. Figures 2(b)–2(g) present the temporal evolution of Φ_p , Φ_{e^-} , Φ_{e^+} , and $\Phi_{\bar{p}}$ in the rigidity range [1.00–1.92] GV. As seen, all four fluxes exhibit complex temporal structures. However, the temporal structures of $\Phi_{\bar{p}}$ are distinctly different from that of the other elementary particle fluxes. Figures 2(b) and 2(c) compare particles with opposite charge but identical mass. As seen, the difference in the temporal variation between $\Phi_{\bar{p}}$ and Φ_p is much greater than between Φ_{e^-} and Φ_{e^+} . Similarly, Figs. 2(d) and 2(e) compare particles with identical charge but different masses. As seen, the difference in the temporal variation between Φ_{e^-} and $\Phi_{\bar{p}}$ is much larger than that between Φ_{e^+} and Φ_p , despite the same difference in mass. Figures 2(f) and 2(g) compare the fluxes of antiparticles and particles. As seen, the difference in the temporal variations between $\Phi_{\bar{p}}$ and Φ_{e^+} is also distinct from that between Φ_p and Φ_{e^-} . These observations indicate the important modulation effects of the spectral shape, in

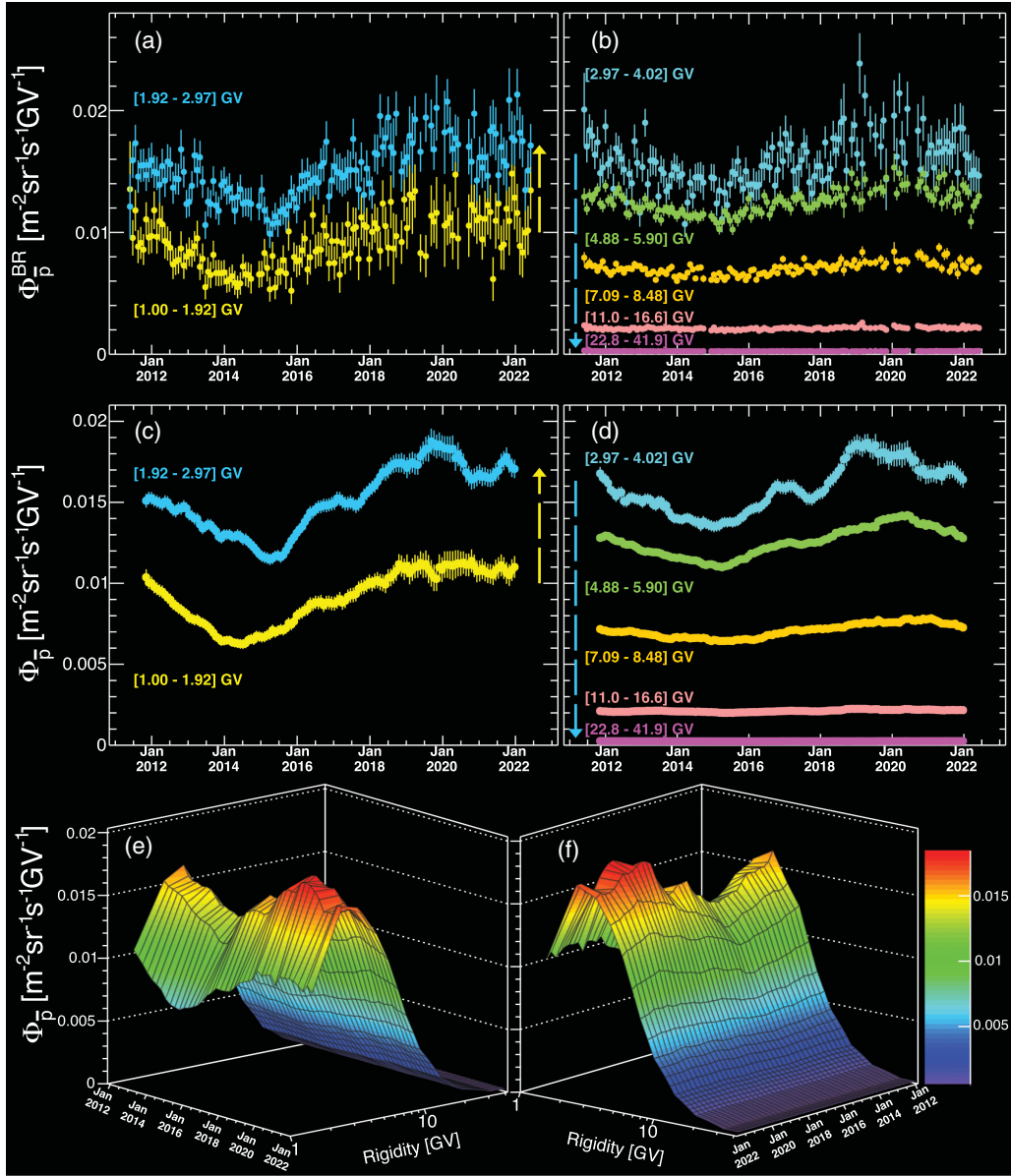


FIG. 1. Temporal evolution of Φ_p^{BR} for (a) below 2.97 GV where the fluxes Φ_p^{BR} increase with increasing rigidity and (b) above 2.97 GV where the fluxes Φ_p^{BR} decrease with increasing rigidity, as indicated by the arrows. (c) and (d) present the Φ_p using their 13-BR moving average values. The data point for each Bartels rotation period is calculated from a time window of 13 BR centered around that period, taking into account the correlation in the systematic errors. In (a)–(d), the error bars are the quadratic sum of the statistical and time-dependent systematic errors. As seen, over a Solar cycle of 11 years, Φ_p exhibit significant temporal variation up to ~ 10 GV and the relative magnitudes of the flux temporal variations decrease with increasing rigidity. Above ~ 10 GV, the flux variations are not visible. In (e) and (f), the three-dimensional variation of Φ_p as functions of time and rigidity is shown.

addition to the modulation effects from particle mass and charge sign.

The long-term variations on the scale of years are related to the 11- and 22-year cycles of the solar magnetic field [1]. Previously, AMS studied the differences in the modulation of Φ_p , Φ_{e^-} , and Φ_{e^+} , using their correlation in time and observed a hysteresis behavior between Φ_{e^-} and Φ_p [35] and Φ_{e^-} and Φ_{e^+} [36], but a linear relation between Φ_{e^+} and Φ_p [36]. With the antiproton results, AMS is able to study

the correlation among all four elementary particle fluxes and measure the differences in their modulation. Figure 3 summarizes the flux correlations between elementary particles in the rigidity range [1.00–2.97] GV [34–36].

As seen in Fig. 3(a), Φ_p and Φ_p exhibit a hysteresis behavior, such that, at a given Φ_p , Φ_p shows two distinct branches over time, one before 2014–2015 and one after. This behavior is similar to the hysteresis behavior between Φ_{e^-} and Φ_{e^+} shown in Fig. 3(b). The hysteresis behavior

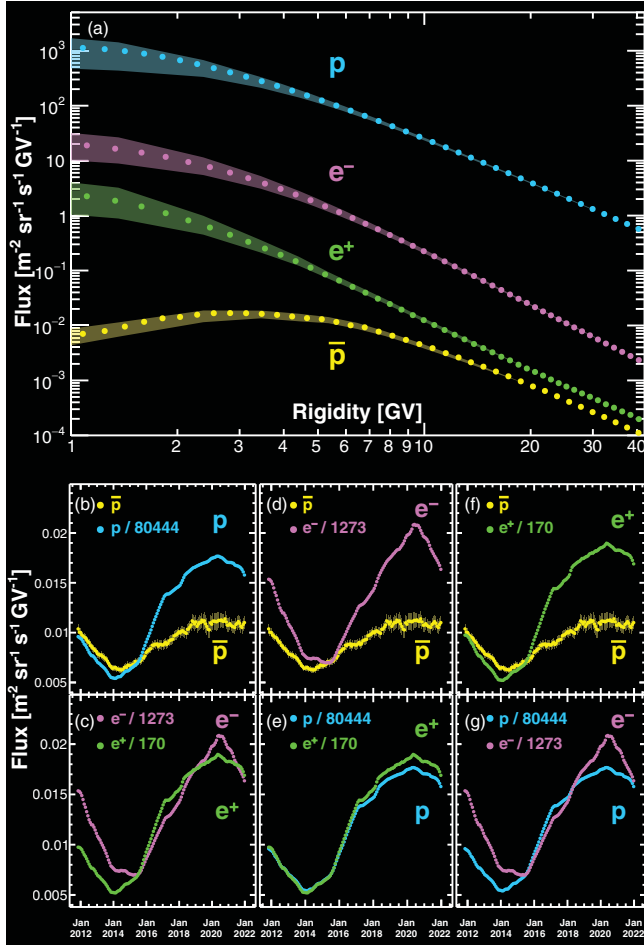


FIG. 2. (a) The 11-year time-averaged fluxes of $\langle\Phi_{\bar{p}}\rangle$ (yellow points), $\langle\Phi_{e^+}\rangle$ (green points), $\langle\Phi_{e^-}\rangle$ (magenta points), and $\langle\Phi_p\rangle$ (blue points). The ranges of the flux temporal variation during this period are shown as shaded bands. In (b)–(g), the temporal evolutions of cosmic elementary particle fluxes in the rigidity range 1.00–1.92 GV for $\Phi_{\bar{p}}$ (yellow points), Φ_p (blue points), Φ_{e^+} (green points), and Φ_{e^-} (magenta points) are compared. As seen, all four fluxes exhibit complex temporal structures, and $\Phi_{\bar{p}}$ is distinctly different from all other elementary particle fluxes. For (b)–(g), each data point represents the 13-BR moving average flux. Φ_p , Φ_{e^+} , and Φ_{e^-} are scaled as indicated such that all fluxes are of the same magnitude on average during 2015.

between $\Phi_{\bar{p}}$ and Φ_p is studied following the method described in Ref. [35] and is compared with the hysteresis behavior between Φ_{e^-} and Φ_{e^+} as detailed in Supplemental Material [51]. As seen in Fig. S4, in each rigidity bin below 11.0 GV, a hysteresis between $\Phi_{\bar{p}}$ and Φ_p is observed. The hysteresis behavior between particles with identical mass but opposite charge sign shows a clear charge-sign effect in the solar modulation. Furthermore, as seen in Table SA and Fig. S5, below 4.88 GV the detailed hysteresis behavior between $\Phi_{\bar{p}}$ and Φ_p is different from the hysteresis behavior between Φ_{e^-} and Φ_{e^+} by more than 4σ significance.

Figure 3(c) shows a linear relation between $\Phi_{\bar{p}}$ and Φ_{e^-} . This behavior is similar to the linear relation between Φ_p

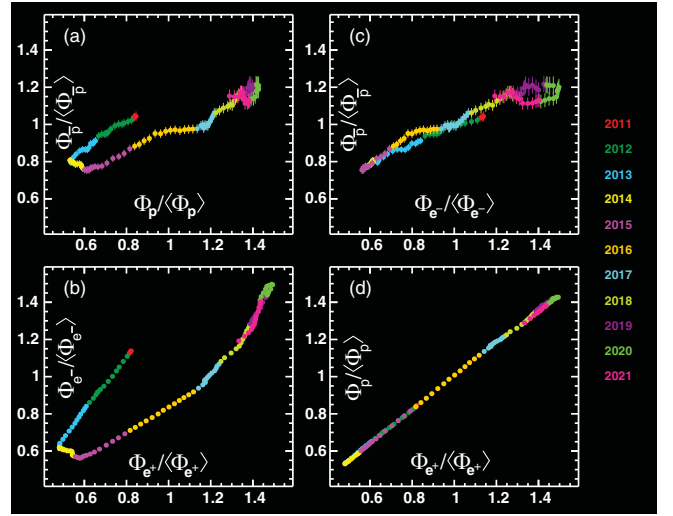


FIG. 3. Correlation between elementary particle fluxes in the rigidity range from 1.00 to 2.97 GV for (a) $\Phi_{\bar{p}}$ and Φ_p , (b) Φ_{e^-} and Φ_{e^+} , (c) $\Phi_{\bar{p}}$ and Φ_{e^-} , and (d) Φ_p and Φ_{e^+} . The data points correspond to flux values of 13-BR moving averages and are normalized to their respective time-averaged value $\langle\Phi\rangle$ over the 11-year period. Different colors indicate different years. As seen in (a) and (b), the flux correlations between particles with opposite charge sign but identical mass exhibit distinct hysteresis behaviors. In contrast, (c) and (d) show that the flux correlations between particles with the same charge sign but different masses exhibit linear relations. Note that, in (a) and (c), the fine structures within the timescale of one year are mostly due to the statistical fluctuations of $\Phi_{\bar{p}}$ and are not significant. Note that in this figure the horizontal error bars are smaller than the symbols.

and Φ_{e^+} shown in Fig. 3(d). The relation between $\Phi_{\bar{p}}$ and Φ_{e^-} is analyzed as described in Supplemental Material [51] and presented in Figs. S6 and S7. As seen, the linear relation between $\Phi_{\bar{p}}$ and Φ_{e^-} is observed for all rigidity bins between 1.00 and 7.09 GV, where $\Phi_{\bar{p}}$ is modulated significantly less than Φ_{e^-} . In comparison, the linear relation between Φ_p and Φ_{e^+} shows that their temporal variations are more similar, while Φ_p is also modulated less than Φ_{e^+} [36]. These observations show that particles with the same charge sign are modulated similarly but with differences in their temporal variation originating from mass and spectral shape. Since the difference in mass between p and e^+ is the same as between \bar{p} and e^- , the difference between the linear relations of $\Phi_{\bar{p}}$ versus Φ_{e^-} and Φ_p versus Φ_{e^+} , as seen in Figs. 3(c) and 3(d) and in Fig. S7, shows the importance of the spectral shape in solar modulation.

To study the modulation effects from the spectral shape, we perform a model-independent analysis using the spectral indices of the 11-year time-averaged fluxes and the magnitude of flux temporal variation. The spectral indices γ of elementary particle fluxes are determined from

$$\gamma = d[\log(\Phi)]/d[\log(R)]. \quad (2)$$

Figure S8 in Supplemental Material [51] shows the spectral indices for $\bar{p}(\gamma_{\bar{p}})$, $p(\gamma_p)$, $e^-(\gamma_{e^-})$, and $e^+(\gamma_{e^+})$ as a function of rigidity. They are determined from the 11-year time-averaged fluxes using sliding rigidity windows of 5–7 bins chosen to have sufficient sensitivity to the spectral index. As seen, $\gamma_{\bar{p}}$ exhibits distinct behavior compared to other particles. Below ≈ 3 GV, $\gamma_{\bar{p}} > 0$, that is, the anti-proton fluxes increase with increasing rigidity. For each rigidity bin, $\gamma_{\bar{p}} > \gamma_{e^-}$ and $\gamma_p > \gamma_{e^+}$, but the difference between $\gamma_{\bar{p}}$ and γ_{e^-} is much larger than that between γ_p and γ_{e^+} .

To quantify the flux variation range over this 11-year Solar cycle, for each particle and in each rigidity bin, the 13-BR moving average fluxes are used to define the relative magnitude of the flux variation (M) as the ratio between the maximum flux value and the minimum flux value over the 11-year period. Figure S9 in Supplemental Material [51] presents the magnitude of flux temporal variations for $\bar{p}(M_{\bar{p}})$, $p(M_p)$, $e^-(M_{e^-})$, and $e^+(M_{e^+})$ as a function of rigidity. As seen, below 4.02 GV, $M_{\bar{p}}$ is much smaller than others. Furthermore, $M_{\bar{p}} < M_{e^-}$ and $M_p < M_{e^+}$, but the difference between $M_{\bar{p}}$ and M_{e^-} is larger than that between M_p and M_{e^+} .

Figure 4(a) presents M versus γ for negatively charged particles \bar{p} and e^- and positively charged particles p and e^+ . Remarkably, for each rigidity bin, M versus γ exhibits the same dependence for negatively and positively charged particles as indicated by the dashed lines. As seen, $M_{\bar{p}} < M_{e^-}$ while $\gamma_{\bar{p}} > \gamma_{e^-}$, and $M_p < M_{e^+}$ while $\gamma_p > \gamma_{e^+}$. Figure 4(b) shows the ratios of the difference in M (ΔM) to the difference in γ ($\Delta\gamma$) between negatively charged particles e^- and \bar{p} [$\Delta M(e^-, \bar{p})/\Delta\gamma(e^-, \bar{p})$] and between positively charged particles e^+ and p [$\Delta M(e^+, p)/\Delta\gamma(e^+, p)$] up to 11 GV. As seen, the ratios are less than zero; that is, the flux with a larger spectral index has a smaller variation magnitude. The ratios approach zero with increasing rigidity, indicating that the influence of the spectral shape on flux variation magnitude is decreasing with increasing rigidity. Most importantly, the ratios determined from positively and negatively charged particles are the same within the errors, revealing a universal relation between flux variation magnitude and spectral index, independent of the charge sign. This universal relation shows that the differences in modulation between \bar{p} and e^- and between p and e^+ are mainly due to the difference in their spectral shape. These results on the effect of spectral shape in solar modulation provide crucial input to understand the anti-proton local interstellar spectrum.

In conclusion, we presented the AMS measurements over an 11-year Solar cycle of cosmic antiprotons based on 1.1×10^6 events in the rigidity range from 1.00 to 41.9 GV. The temporal variations of the fluxes of all cosmic charged elementary particles, \bar{p} , p , e^- , and e^+ , are studied simultaneously. Compared to p , e^- , and e^+ , the \bar{p} fluxes exhibit

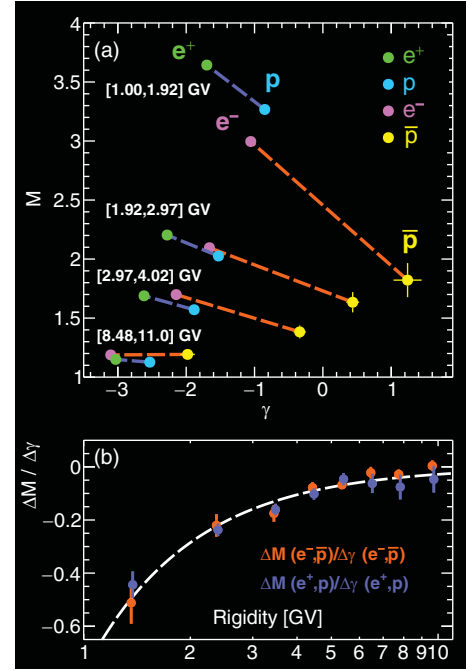


FIG. 4. (a) The magnitude of flux temporal variation M versus the spectral index γ of \bar{p} (yellow points), e^- (magenta points), p (light blue points), and e^+ (green points), for four typical rigidity bins. For each rigidity bin, the dashed lines connect particles with the same charge sign and show the dependence between M and γ . As seen, the dependence is the same for (e^-, \bar{p}) and for (e^+, p) : $M_{\bar{p}} < M_{e^-}$ while $\gamma_{\bar{p}} > \gamma_{e^-}$ (orange lines), and $M_p < M_{e^+}$ while $\gamma_p > \gamma_{e^+}$ (dark blue lines). (b) The ratios of the difference in M (ΔM) to the difference in γ ($\Delta\gamma$) between e^- and \bar{p} [$\Delta M(e^-, \bar{p})/\Delta\gamma(e^-, \bar{p})$, orange points] and between e^+ and p [$\Delta M(e^+, p)/\Delta\gamma(e^+, p)$, dark blue points] as a function of rigidity. As seen, $\Delta M(e^-, \bar{p})/\Delta\gamma(e^-, \bar{p})$ and $\Delta M(e^+, p)/\Delta\gamma(e^+, p)$ are the same within the errors, revealing a universal relation independent of the charge sign. In (b), the horizontal positions for $\Delta M(e^+, p)/\Delta\gamma(e^+, p)$ are displaced slightly for clarity. The white dashed curve is to guide the eye.

distinct properties. The magnitude of the \bar{p} flux temporal variation is significantly smaller than those of p , e^- , and e^+ . A hysteresis between the \bar{p} fluxes and the p fluxes is observed, whereas the \bar{p} and e^- fluxes show a linear correlation. With a model-independent analysis, we found a universal relation between the shape of the rigidity spectrum and the magnitude of flux temporal variation over an 11-year Solar cycle, independent of the charge sign. These results provide unique information for understanding solar modulation as a function of mass, charge, and spectral shape and essential inputs for the understanding of the origin of antiprotons in the cosmos.

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