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Precision Measurement of Daily Proton and Helium Fluxes by the Alpha Magnetic Spectrometer

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The precision measurement of the daily proton and helium fluxes will be presented. The period of observation covers 11 year solar cycle from the ascending phase through its maximum going toward its minimum. Time variations of the fluxes on different time scales associated to the solar activity are presented. Detailed time variations of fluxes and ratio will be also presented. Remarkably, below 2.4 GV a hysteresis between the helium to proton flux ratio and the helium flux was observed at greater than the 7σ level.

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1. Introduction

The temporal evolution of the interplanetary space environment causes cosmic-ray intensity variations. This is particularly visible at energies below 100 GeV. These variations correlate with solar activity at different time scales [1, 2]. The most significant long-term scale variation is the 11-year solar cycle during which the number of sunspots changes from minimum to maximum and then back to a minimum [3, 4]. Shorter scale variations can be either nonrecurrent or recurrent. The nonrecurrent variations are mainly due to the interactions of cosmic rays with strong transient disturbances in the interplanetary magnetic field, such as shock waves generated by interplanetary coronal mass ejections, especially during solar maxima, that can last from days to weeks [5]. Recurrent variations with a period of 27 days, corresponding to the synodic solar rotation, and at multiples of that frequency (*e.g.*, periods of 13.5 and 9 days) are related to the passage of corotating interaction regions originating from one or more coronal holes of the Sun [6–14], as first observed in 1938 [15]. Previous studies on the estimated rigidity dependence in periodicities, for example in Ref. [11], generally concluded that the power of the periodicity decreases with increasing rigidity. This formed the paradigm over the AMS rigidity range (1 to 100 GV) that the strength of the 27-day (and 13.5-day, 9-day) periodicities steadily decreases with increasing rigidity of cosmic rays. However, recent AMS results on periodicities in proton and helium daily fluxes [16, 17] do not support that the strength of the periodicities would always decrease with increasing rigidity.

Cosmic-ray transport in the heliosphere is rigidity dependent. Hence, the time variation of different particle spectra (p, He, etc.) evaluated at the same rigidity are expected to exhibit a similar behavior. However, according to models based on the Parker equation [1], the time dependence of distinct nuclei fluxes evaluated at the same rigidity might differ because of (a) differences in the flux rigidity dependence outside the heliosphere, (b) differences in velocity because of distinct mass-to-charge ratio [18], and (c) solar wind turbulence and other interplanetary parameters.

2. Periodicities in the Daily Proton Fluxes

We present the daily time evolution of the proton flux from 1.00 to 100 GV. The measurement is based on 6.3×10^9 protons collected by AMS during the first 10.5 years (May 20, 2011 to November 2, 2021) of operation. This is an update of the published AMS daily proton fluxes based on the first 8.5 years of operation in Ref. [16].

Figure 1 shows the daily proton fluxes for six rigidity bins. As seen, the proton fluxes exhibit variations on different time scales, from days to years. The relative magnitude of these variations decreases with increasing rigidity. At low rigidities, recurrent flux variations are clearly visible.

To study the recurrent time variations in the daily proton fluxes, a wavelet time-frequency technique [19] was used to locate the time intervals where the periodic structures emerge. We observed recurrent flux variations with a period of ~27 days with significance above the 95% confidence level from 2014 to 2018. Shorter periods of ~13.5 days and ~9 days are significant only in 2016.

Figure 2 shows the normalized power as a function of rigidity and period for the first and the second half of 2016. As seen, the strength of all three periodicities is rigidity dependent. In particular, the strength of 9-day and 13.5-day periodicities increases with increasing rigidity up to

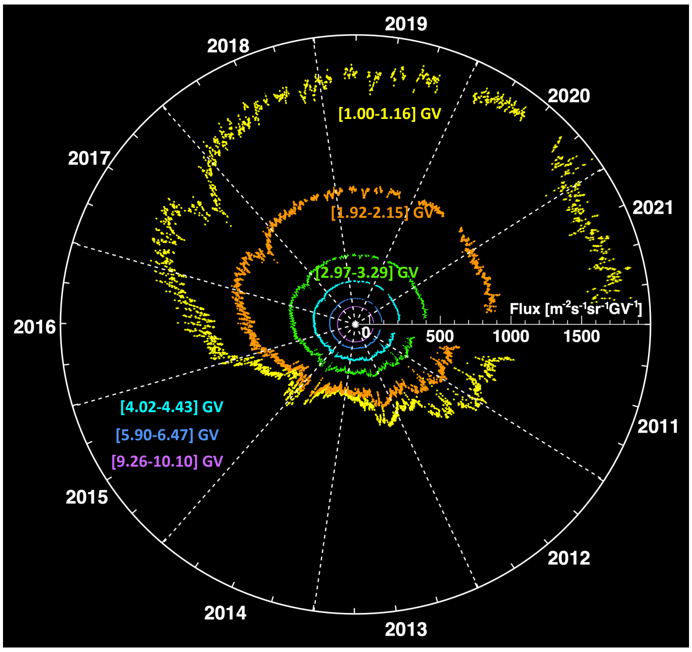

Figure 1: The daily AMS proton fluxes for six rigidity bins measured from May 20, 2011 to November 2, 2021.

10 GV and 20 GV, respectively, and then decreases with increasing rigidity up to 100 GV. Thus, the AMS results do not support the general conclusion that the strength of the periodicities steadily decreases with increasing rigidity.

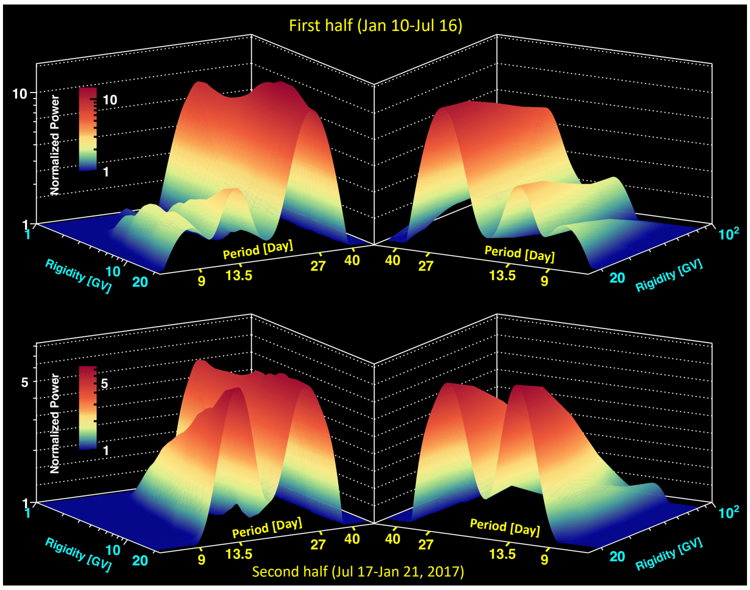

Figure 2: The normalized power as a function of rigidity and period for (a) the first and (b) the second half of 2016 from 1 to 20 GV and from 20 GV to 100 GV.

The intensity variations of cosmic rays are caused by the temporal evolution of the interplanetary space environment. Figure 3 shows the comparison of the AMS daily proton fluxes at [5.90-6.47] GV and the speed of solar wind [20] in the second half of 2016. As seen, the proton fluxes are observed to be related to the speed of solar wind for the 13.5-day periodicity in this period.

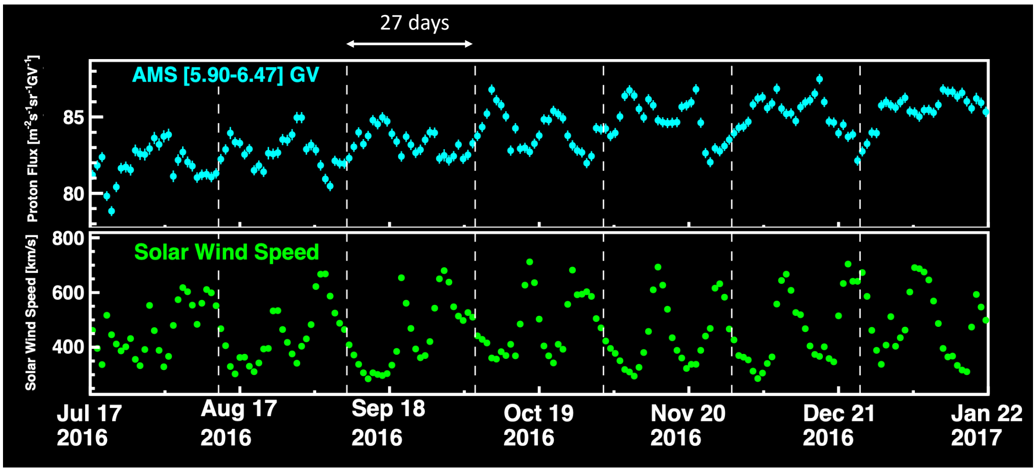

Figure 3: The comparison of the AMS daily proton fluxes at [5.90-6.47] GV and the speed of solar wind [20] in the second half of 2016. Vertical dashed lines separate Bartels rotations.

3. Properties of Daily Helium Fluxes

We also present the daily time evolution of the helium flux from 1.71 to 100 GV. The measurement is based on 8.9 $\times 10^8$ helium nuclei collected by AMS during the first 10.5 years of operation. This is an update of the published AMS daily helium fluxes based on the first 8.5 years of operation in Ref. [17].

To study the recurrent time variations in the helium flux, Φ_{He}, a wavelet time-frequency technique [19] was used to locate the time intervals where the periodic structures emerge. Similar periodic structures as shown in the previous section for the daily proton fluxes also have been observed in the daily helium fluxes.

Figure 4 shows Φ_{He}, Φ_p, and $\Phi_{\mathrm{He}}/\Phi_p$ as a function of time for the rigidity bin [1.71-1.92] GV. As seen, $\Phi_{\mathrm{He}}/\Phi_p$ ehibits variations on multiple timescales. On short scales, $\Phi_{\mathrm{He}}/\Phi_p$ has a dip lasting months corresponding to the dip observed in Φ_{He}. On long timescales, the $\Phi_{\mathrm{He}}/\Phi_p$ reaches a minimum in 2013 – 2014, when the Φ_{He} is also in its minimum, and a maximum in 2018 – 2019, when the Φ_{He} is also in its maximum.

We study the variation on the flux ratio $\Phi_{\mathrm{He}}/\Phi_p$ averaged over the period (2018-2019) and ratio $\Phi_{\mathrm{He}}/\Phi_p$ averaged over the period (2013-2014) as a function of rigidity. As shown in Fig. 5, $\Phi_{\mathrm{He}}/\Phi_p$(2018-2019) > $\Phi_{\mathrm{He}}/\Phi_p$(2013-2014) for rigidities below ~7 GV. This implies that Φ_{He}(2018-2019)/Φ_{He}(2013-2014) > Φ_p(2018-2019)/Φ_p(2013-2014); i.e., Φ_{He} exhibits larger time variations than Φ_p at low rigidities. As seen in the figure $\Phi_{\mathrm{He}}/\Phi_p$ is time independent above ~7 GV.

To investigate the difference of modulation in helium fluxes and proton fluxes, we consider in detail daily $\Phi_{\mathrm{He}}/\Phi_p$ as a function of daily Φ_{He}. Figure 6 shows $\Phi_{\mathrm{He}}/\Phi_p$ as a function of daily

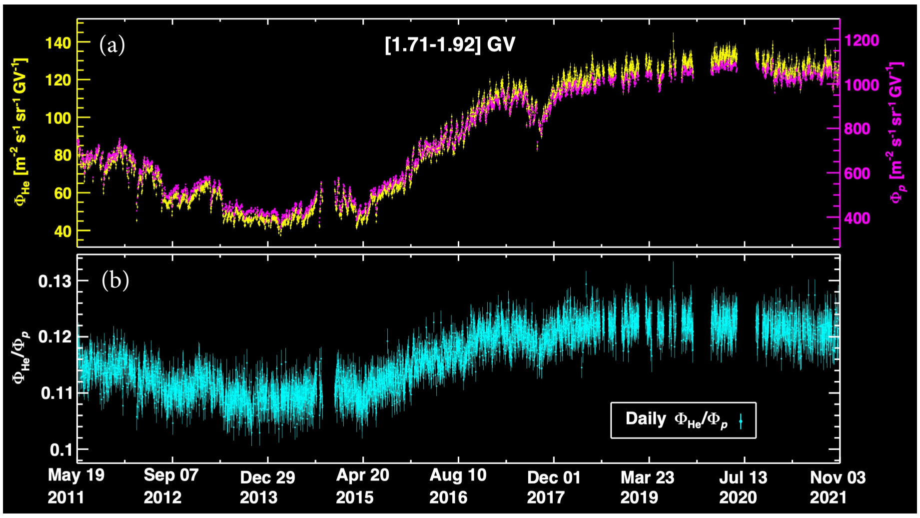

Figure 4: (a) Φ_{He} (yellow) and Φ_p (magenta) and (b) $\Phi_{\mathrm{He}}/\Phi_p$ (cyan) measured from May 20, 2011 to November 2, 2021 at [1.71 – 1.92] GV.

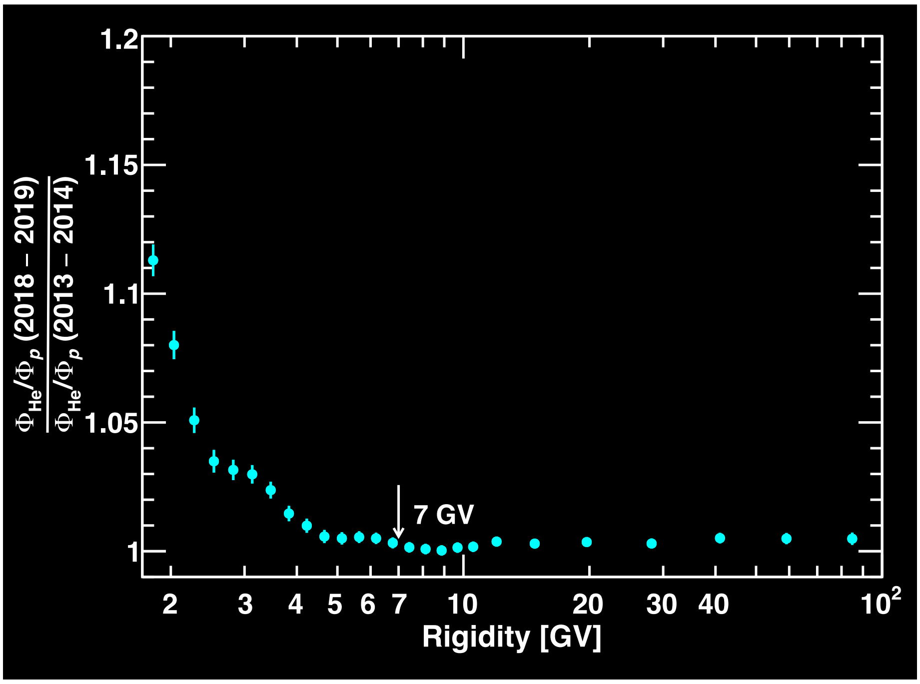

Figure 5: The ratio of the two flux ratios: $\Phi_{\mathrm{He}}/\Phi_p$ averaged over period (2018-2019) and $\Phi_{\mathrm{He}}/\Phi_p$ averaged over period (2013-2014) as a function of rigidity.

Φ_{He} both calculated with the moving average of 14 Bartels rotations with a step of one day for the rigidity bin [1.71-1.92] GV. As seen in Fig. 6, below 2.4 GV, a hysteresis between $\Phi_{\mathrm{He}}/\Phi_p$ and Φ_{He} is observed before and after the solar maximum in 2014. To assess the significance of this hysteresis, we study the difference (in units of σ) of $\Phi_{\mathrm{He}}/\Phi_p$ at the same Φ_{He} but different solar conditions. The hysteresis is observed at greater than the 7σ level below 2.4 GV. This shows that at low rigidity the modulation of $\Phi_{\mathrm{He}}/\Phi_p$ is different before and after the solar maximum in 2014. These unexpected observations provide inputs to the understanding of cosmic-ray propagation in the heliosphere and its dependence on rigidity, on velocity, on solar wind turbulence, and on other interplanetary parameters.

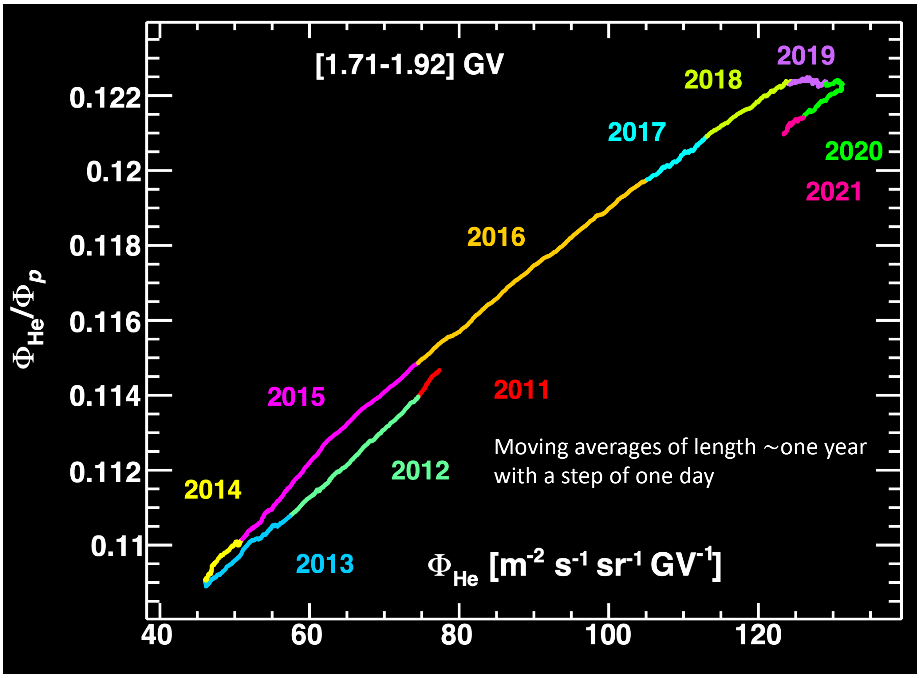

Figure 6: $\Phi_{\mathrm{He}}/\Phi_p$ as a function of Φ_{He} both calculated with a moving average of length 14 Bartels rotations with a step of one day for the rigidity bin [1.71-1.92] GV. Different colors indicate different years from 2011 to 2021.

4. Summary

In summary, the proton and helium fluxes exhibit variations on different time scales, in days, months, and years. From 2014 to 2018, we observed recurrent flux variations with a period of 27 days. Shorter periods of 9 days and 13.5 days are observed in 2016. The strength of all three periodicities changes with both time and rigidity. Unexpectedly, the strength of 9-day and 13.5-day periodicities increases with increasing rigidity up to 10 GV and 20 GV, respectively. Then the strength of the periodicities decreases with increasing rigidity up to 100 GV. Similar periodic structures also have been observed in the daily helium fluxes. In the entire time period, we found that below ~7 GV the helium flux exhibits larger time variations than the proton flux. Remarkably, below 2.4 GV, a hysteresis between the helium to proton flux ratio and the helium flux was observed at greater than the 7σ level. This shows that at low rigidity the modulation of the helium to proton flux ratio is different before and after the solar maximum in 2014. These new precision measurements provide unique inputs to the understanding of cosmic rays in the heliosphere.

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