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Comparison of Cosmic Ray Spectral Variation during 2015-2019 as Indicated by the South Pole Neutron Monitor Leader Fraction and AMS-02 Spectral Index

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From histograms of time delays between counts in a neutron monitor, one can extract the leader fraction, L, of neutron counts that did not follow a previous neutron count in the same counter tube associated with the same cosmic ray shower. The leader fraction is the inverse of the neutron multiplicity and can indicate variations in the cosmic ray spectral index over a certain rigidity range above the local cutoff. Here we calibrate L from the South Pole neutron monitor, with an atmospheric cutoff of $\sim$ 1 GV, with respect to a daily spectral index determined using published data from the Alpha Magnetic Spectrometer (AMS-02) aboard the International Space Station for Galactic cosmic ray proton fluxes during 2015-2019. We find that the leader fraction is well correlated with the daily proton spectral index fit over 2.97-16.6 GV as inferred from AMS-02. We estimate the uncertainty in the spectral index as inferred from the leader fraction. This work verifies that the ground-based neutron monitor network can perform precise and continuous monitoring of cosmic ray spectral variations in the long-term future.

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1. Introduction

The neutron monitors (NMs) are ground-based detectors of secondary particles produced in atmospheric cascades from primary cosmic ray ions, which are mostly Galactic cosmic rays (GCRs). The South Pole (SP) NM, at an altitude of 2828 m, has three 1NM64 detectors. They have ^{3}He gas proportional counters, which are sensitive to the neutrons produced by the interaction of the secondary particles with a dense lead producer. Monitoring the count rate C provides information about variations of the cosmic ray flux entering at the top of the atmosphere. The most significant long-term variation is solar modulation according to the 11-year sunspot cycle and the ~22-year solar magnetic cycle. Short-term variations are mainly due to solar activity, such as interplanetary coronal mass ejections, or the ~27-day and daily variations related to the solar rotation and the Earth's rotation, respectively.

The SP NM was able to record histograms of time delays between successive neutron counts in the same counter tube since 2013, which relate to the multiplicity. These provide information about variations in the cosmic ray spectrum [1]. Previous work developed techniques to remove the effect of chance coincidences and extract the "leader fraction" L of neutron monitor counts that did not follow other counts in the same counter tube from the same cosmic ray shower [1–3].

This work reports the measurement of the leader fraction of the South Pole NM from March 2015 - March 2023. We determined the proton spectral index using data from the Alpha Magnetic Spectrometer (AMS-02), a high-energy particle detector deployed on the International Space Station (ISS). We also calibrated SP L with the AMS-02 proton spectral index during 2015-2019 and present predictions of the proton spectral index that will be inferred later when AMS-02 data become public.

2. Leader fraction of neutron monitor

Using neutron time-delay data from a single station with these specialized electronics, we can indicate variations in the cosmic-ray spectral index [1]. The SP NM started using electronic firmware to record the time-delay histograms on one NM tube in 2013 December and the complete set of 3 counter tubes in 2015 March. Figure 1 shows an example of hourly time-delay histograms over long and short time scales from SP NMs on January 1, 2016.

For long time delays, the histogram has an exponential tail representing chance coincidences between two unrelated incoming secondary particles (mostly neutrons). For short time delays (< 2ms), the histogram exhibits a non-exponential distribution, which can be attributed to time associated neutron counts that originated from the same cosmic ray. We determined L from the time-delay histogram following following formula [1] without overflow by: $L = A/(\alpha e^{\alpha t_d})$ where A and α are the parameters from the long time-delay histogram fitted to $n(t) = Ae^{-\alpha t}$ of the exponential of time delay t and t_d is the effective electronic dead time.

Most of the NMs appear very stable and suitable for studies of long-term solar modulation of cosmic rays. However, atmospheric pressure strongly affects the NM count rate and L. In Antarctica, effect of atmospheric water vapor pressure is very low. The pressure variations are anti-correlated with the NM count rate. In contrast, There are positive correlations with L. We use the standard barometric correction developed previously, by which L is multiplied by $\exp[-\beta(P-P_0)]$, where β is a pressure coefficient and P_0 is a reference pressure (680 hPa). To find the pressure

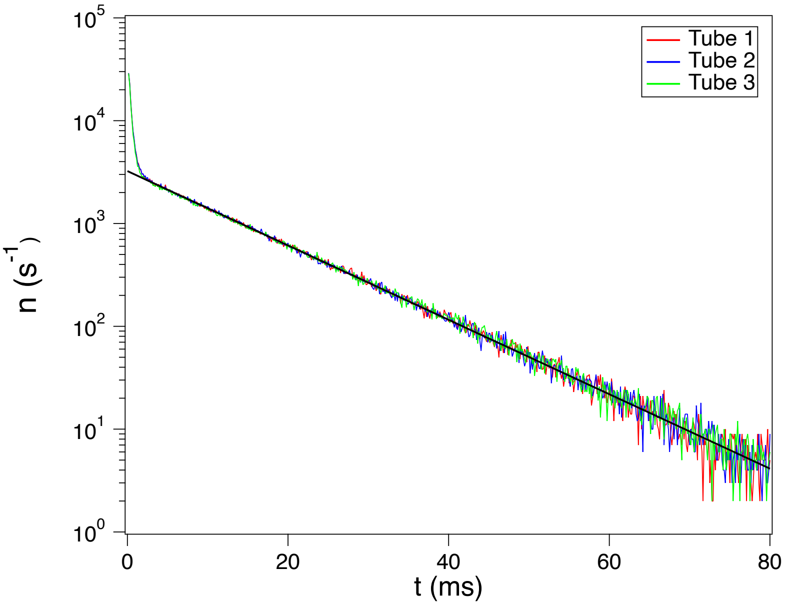

Figure 1: Example of time-delay histograms for the South Pole NMs during one hour. Long time delays show an exponential distribution (black line) as expected for unrelated neutron detection events. At short time delays (<2 ms), the distribution deviates substantially from that exponential because many events are related, coming from the same atmospheric secondary particle that interacts in the monitor, usually in the lead producer. Color indicates the NM tube.

coefficient of L, we used a linear fit to $\Delta \ln L$ versus ΔP, where “Δ” indicates the difference from a 13-day running average. The different firmware and data acquisition systems give different β values for each counter tube. The mean value of β is 0.0187% hPa^{-1}. The variations in L and C generally have the same trend in solar modulation but SP L is weak in 27-day and ~13.5-day modulation [4].

3. Comparative Results

In order to compare SP L with the cosmic ray spectral index, we calculate the spectral index by using a power-law fit of daily proton flux as a function of rigidity over a specific range. The AMS-02 detector provided the measurement of daily proton fluxes in cosmic rays in rigidity intervals from 1 to 100 GV [5] up to October 29, 2019. We found a strong correlation between SP L and the spectral index inferred from power-law fitting of daily AMS-02 proton fluxes over the rigidity range 2.97–16.6 GV from March 03, 2015 to October 29, 2019.

To better compare variations, both SP L and the AMS-02 proton spectral index were normalized as (data - average)/(standard deviation). The result in figure 2 shows that the variations track each other well. SP L has a higher fluctuation than the AMS-02 proton spectral index. It is clear that SP L variations at times move from high to low around the AMS-02 proton spectral index, which may be caused by seasonal effects near the South Pole. However, these seasonal variations are much weaker than the solar modulation effect, and are not corrected in this analysis. The relation between the AMS-02 proton spectral index and SP L is approximately a linear relation. We can convert SP L to estimate of the spectral index from $\gamma = -36.47 + 51.48(\text{SP } L)$. To assess the quality of linear

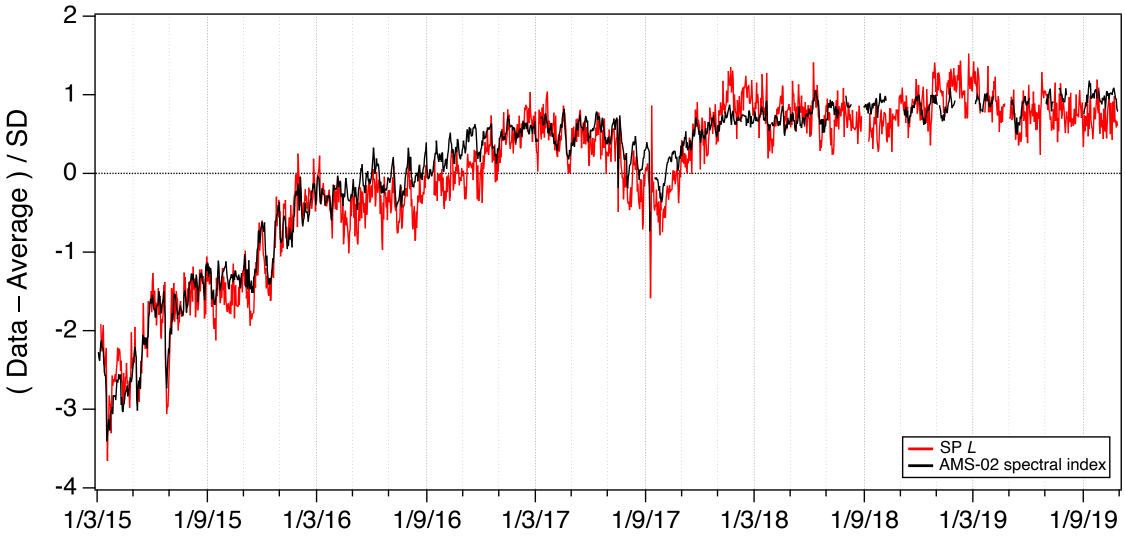

Figure 2: The normalized SP L (red) and AMS-02 proton spectral index (2.97–16.6 GV, black) from March 3, 2015 to October 29, 2019.

fitting, we calculated the difference between the predicted AMS-02 proton spectral index (fitting line) and the AMS-02 proton spectral index (obtained from the power-law fit). We then used this difference to find the residual standard deviation, which is approximately equal to 0.019. This can be considered as indicative of satisfactory quality.

Results in figure 4 present the SP leader fraction L and count rate C from Mar 3, 2015, to March 3, 2023. The AMS-02 proton spectral index over the rigidity range 2.97–16.6 GV is about 2.1 during solar maximum (2015) and about 2.4 during solar minimum (2020). SP L and the AMS-02 proton spectral index (black line) has increased from 2015 to the time of high GCR flux in 2020 and decreased thereafter. Overall, GCR count rate and spectral index mainly vary with the same trends. There are some different variations in smaller time scales. In addition, the AMS-02 proton spectral index and SP L variation are similar. The spectral index (magenta line) as estimated from SP L has higher fluctuation compared with the AMS-02 proton spectral index (black line). In any case, the approximately linear relation between SP L and AMS-02 proton spectral index confirms that SP L serves as a ground-based proxy of the proton spectral index to within a precision of ±0.019.

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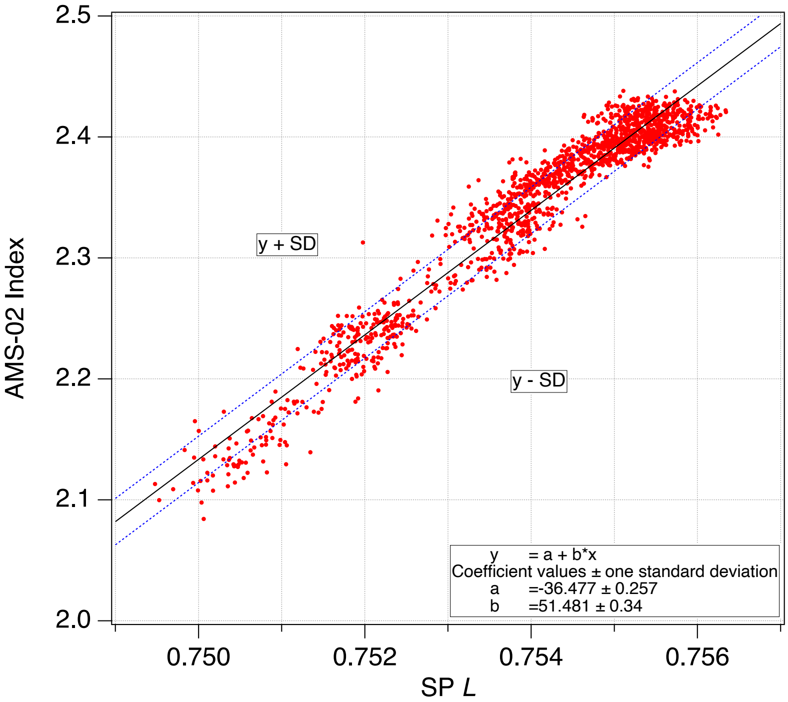

Figure 3: AMS-02 proton spectral index (2.97–16.6 GV) versus SP L. Black line is the linear fit. Blue dashed lines are vertically displaced by one standard deviation to indicate the uncertainty in using L to estimate the spectral index.

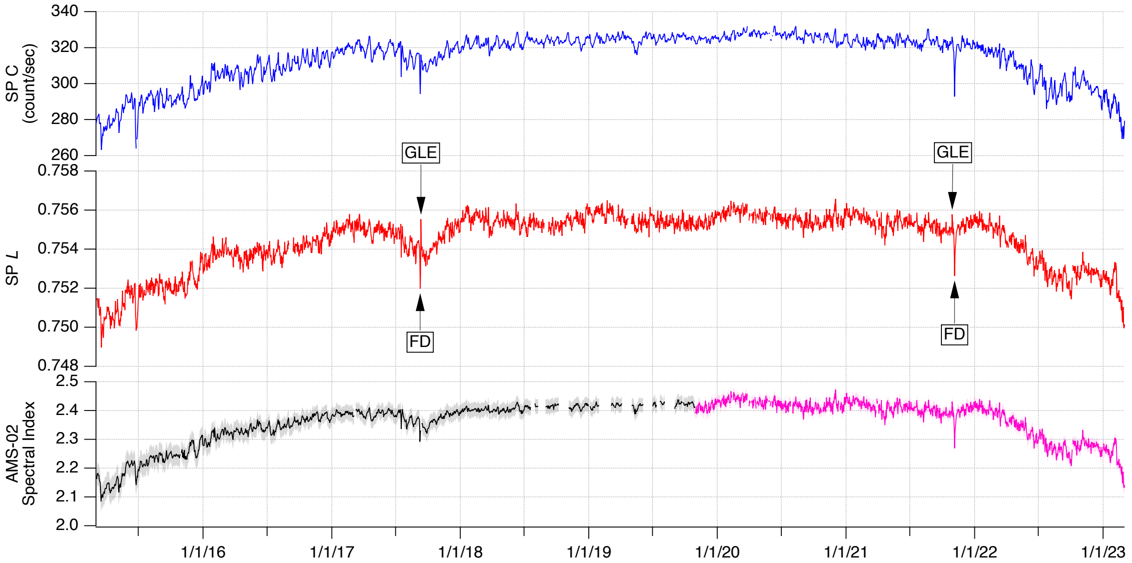

Figure 4: Top panel: South Pole neutron monitor count rate from Mar 3, 2015 to March 3, 2023. middle panel: SP L, a proxy to the spectral index. Bottom panel: Black line is AMS-02 proton spectral index (2.97–16.6 GV, black) from Mar 03, 2015 to October 29, 2019. Grey shading above and below the black line indicates uncertainty of the power law fitting. The magenta line is the predicted spectral index from SP L from October 30, 2019 to March 03, 2023. Shading indicates the uncertainty.

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