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Solar Magnetic Polarity Effect on Neutron Monitor Count Rates: Comparing Latitude Surveys and Antarctic Stations

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The Galactic cosmic ray spectrum manifests pronounced variations over the 11-year sunspot cycle and more subtle variations over the 22-year solar magnetic cycle. An important tool to study these variations is repeated latitude surveys with neutron monitors onboard icebreakers in conjunction with land-based references. We revisit 13 annual latitude surveys from 1994 to 2007 using reference data from Mawson instead of McMurdo (closed in 2017). We then consider two more latitude surveys (2018 and 2019) with a monitor similar to the 3NM64 in the previous surveys but without lead rings around the central tube, a so-called "semi-leaded neutron monitor." The new surveys extend the linear relationship among data taken at different cutoff rigidity. They also confirm the "crossover" in spectra measured near solar minima during epochs of opposite solar magnetic polarity and the absence of crossover for epochs having the same solar magnetic polarity.

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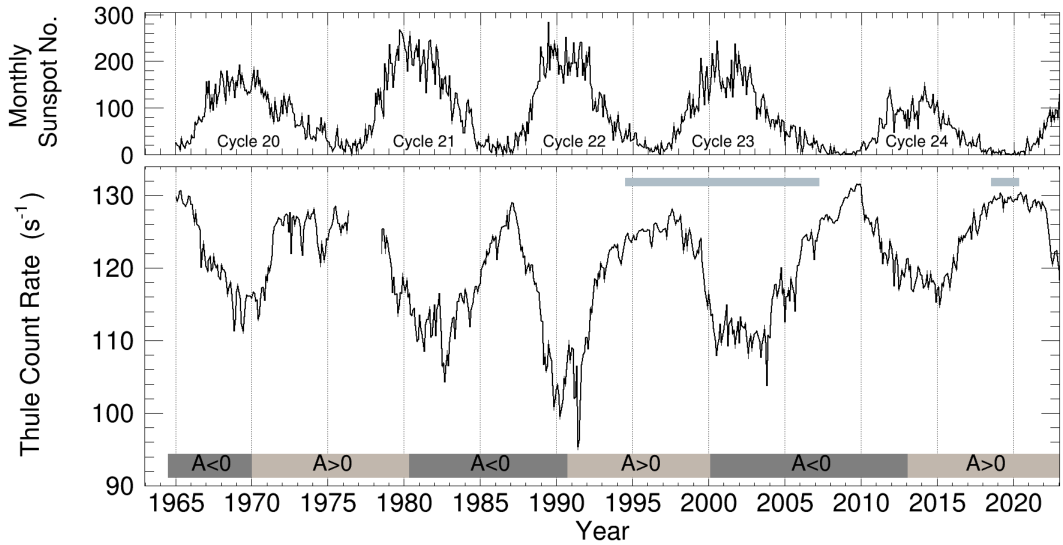

Figure 1: The count rate recorded by a neutron monitor is an indicator of the Galactic cosmic ray flux, which undergoes "solar modulation" related to solar activity [1–3]. As solar activity increases (shown in the top panel, Source: WDC-SILSO Royal Observatory of Belgium, Brussels), the pressure-corrected count rate recorded by the neutron monitor in Thule decreases (bottom panel, Source: Bartol Research Institute, University of Delaware, USA). The solar magnetic polarity reversal can be observed as the polarity shifts between positive (represented by $A > 0$) and negative (represented by $A < 0$) values. This work presents observations for the periods 1994-2007 and 2019-2020, as indicated by horizontal bars between the two panels.

1. Introduction

Galactic cosmic rays (GCRs) are high-energy particles originating from outside our solar system that make their way to Earth. As GCRs enter the heliosphere, they encounter a turbulent magnetic field, leading to significant variations in their intensity and energy levels. The sun's influence on GCR intensity is known as solar modulation. The GCR spectrum undergoes changes that are closely tied to both the sunspot cycle and the solar magnetic cycle. Ground-level observations using neutron monitors and muon detectors provide a record of cosmic ray intensity. The quasi-periodic 11-year cycle in the neutron monitor count rate is related to solar activity, as shown in Figure 1.

The number of sunspots which is referred to as the 11-year cycle of solar activity is caused by the evolution of the solar magnetic field. During an active solar cycle, multiple coronal mass ejections (CMEs) eject high-energy particles from the Galaxy, decreasing count rates on neutron monitors that respond to Galactic cosmic rays in the GeV energy range. Additionally, the polarity of the solar magnetic field reverses approximately every 11 years, with the exact cause remains unknown, but it occurs when the magnetic field is most complex, near solar maximum.

During solar minimum, few sunspots are present. However, during the solar maximum, the number of sunspots increases before dropping again during the subsequent solar minimum. The counting rate recorded by a neutron monitor is inversely correlated with solar activity.

A mobile neutron monitor can rapidly record data across various geomagnetic cutoffs during a "latitude survey" [4]. Latitude surveys can help us understand geomagnetic cutoff rigidity and allow us to track changes in the primary cosmic ray spectrum. Latitude surveys conducted in 1976 and 1987 [5] and 1997 and 2006 [1] demonstrate an intersection of the differential response function, which is called the "crossover," at a rigidity of approximately 5-7 GV, and also measured at solar minima during epochs of opposite magnetic polarity.

The spectral crossover is a change in the cosmic ray energy spectrum during the solar magnetic field reversal. The direction of the curvature drift of charged cosmic ray particles changes due to the polarity reversal, which leads to changes in their energy spectrum because of their altered confinement in the heliosphere. [5] also investigated the relationship between magnetic helicity and the spectral crossover and found that the helicity of the magnetic field was related to the magnitude of the spectral crossover. The spectral crossovers can also be observed through the correlation of neutron monitor count rates from latitude surveys and fixed neutron monitors such as at the McMurdo station [1]. The regression analysis has revealed a consistent trend with slopes that change when the solar magnetic polarity flips, most likely due to a systematic change in the interplanetary diffusion coefficient for cosmic rays.

Due to the relocation of the neutron monitor station from McMurdo to Jang Bogo station, we cannot extend the previous neutron monitor surveys from McMurdo. Instead, we performed a similar analysis using Mawson station's data and confirmed the presence of crossovers. Additionally, we analyzed two recent latitude surveys conducted in 2018 and 2019 using a similar monitor to the 3NM64 used in the previous surveys, but without the lead producer surrounding the central tube, referred to as a "semi-leaded neutron monitor." We present the results of this analysis using the series of 13 annual latitude surveys and two recent latitude surveys to determine the regression with the Mawson neutron monitor station.

2. The Observations

2.1 Mobile Neutron Monitors

Figure 2 shows the routes taken by the mobile neutron monitors employed in this study. Each color corresponds to a "survey year," defined as the year the voyage commenced. The latitude survey undertaken in this study was conducted in two separate periods as follows:

2.1.1 Thirteen Survey Years, 1994–2007

Between 1994 and 2007, surveys were conducted using data from three standard neutron monitors (3NM64) housed within a shipping container nicknamed the "Tasvan." The mobile neutron monitor was operated aboard either the Polar Sea or the Polar Star, two U.S. Coast Guard icebreakers that traveled approximately six-month voyages across the Pacific Ocean, starting from Seattle in the USA and culminating in McMurdo, Antarctica, and back. In our analysis, we utilize count rate data from 13 survey years (1994-2007), which have been corrected for pressure but remain uncorrected for short-term modulation variations with the McMurdo count rate. Additionally, we exclude periods with large Forbush decreases greater than 10%, documented in [1].

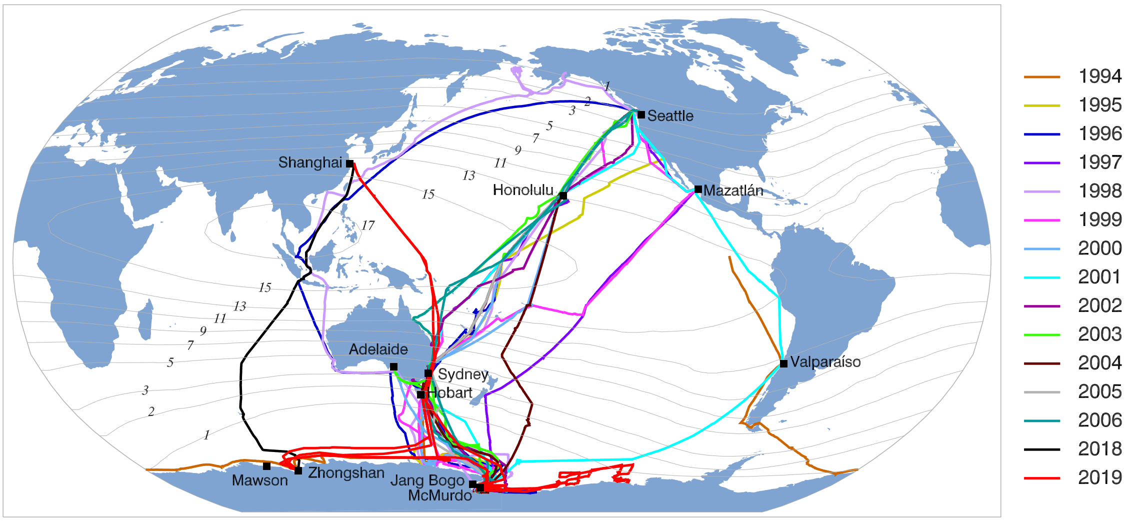

Figure 2: The tracks of the ship-borne neutron monitor latitude surveys conducted during the periods of 1994-2007 [1] and 2019-2020 [6, 7] are overlaid onto a contour map of the vertical cutoff rigidity (GV) calculated for February 11, 2019 at 12:00 UT.

2.1.2 Two Survey Years, 2018–2020

Survey years 2018 and 2019 used two standard neutron monitors flanking one lead-free neutron monitor installed in a shipping container named "Changvan." The container was operated aboard the icebreaking vessel Xuelong, traveling from Shanghai to Zhongshan station in Antarctica. During the 2018 survey year (2 November 2018 – 11 March 2019), the Changvan monitor only collected data on the return journey from Zhongshan station, Antarctica, to Shanghai from 11 February to 11 March 2019. Data were recorded in the 2019 survey year (21 October 2019 – 22 April 2020) to and from Antarctica. For the complete survey data in 2018 and only the southbound data in 2019, we used count rate data provided in [6]. For additional data in the 2019 survey year, we obtained it from [7].

2.2 Fixed Neutron Monitor Stations

2.2.1 McMurdo & Jang Bogo

McMurdo station is a US Antarctic research station situated at the southern tip of Ross Island (77.90°S, 166.6°E), with an altitude of 48 meters above sea level and a vertical cutoff rigidity of less than 0.3 GV. The Cosmic Ray Lab inside the station houses the 18-tube NM64 neutron monitor, which consists of six neutron detector tubes in three sections. The pressure-corrected count rate data used in this analysis were obtained from [1], which used a barometric coefficient (β) of 0.9866 %/mmHg and a reference pressure of 730.00 mmHg in their calculations. The McMurdo station was shut down completely on 7 January 2017. The McMurdo neutron monitor was relocated to the South Korean station at Jang Bogo, Antarctica, located 360 km away from McMurdo station. Initially, we had intended to use data from Jang Bogo to replace the McMurdo station, which had already been closed, to extend our analysis and cover the data from the recent two surveys. However, there was a data gap of about one month (from 5 January to 3 February 2020) and several months of frequent missing data after 19 February 2020. Due to these numerous data gaps, we used the Mawson data (described in subsection 2.2.2) instead. We did, however, refer to the Jang Bogo data (when available) to identify anomalies in the Mawson data.

2.2.2 Mawson

Mawson is situated at the edge of the Eastern Antarctic plateau (67.60 °S, 62.88 °E) and is the first continental station south of the Antarctic Circle. It is also the most extended continuously operating station in this region. The altitude is 30 meters above sea level, and the vertical cutoff rigidity is 0.22 GV. From 1986 to October 16, 2002, the neutron monitor at Mawson had six neutron counters placed in the same NM segment. After October 17, 2002, the system was upgraded to use 18 counter tubes. In early 2020, the data acquisition system at Mawson was updated with new electronic firmware and computer software. However, the preparation of Mawson data is a little complicated due to changes in the number of counter tubes in late 2002. Specifically, the 6NM64 neutron monitor initially operated at Mawson station and later changed to 18NM64 on October 17, 2002. To account for this change, we used a scaling factor of 2.851 to divide the 18NM64 data and convert it to the 6NM64 format.

3. Data Reduction and Correction

We conducted a meticulous data reduction and correction process for the semi-leaded Changvan monitor data. Specifically, we employed a conventional neutron monitor correction method and corrected the pressure data. Initially, we endeavored to derive the pressure-correction equation for the Changvan monitor using data from the two survey years. However, the results did not differ significantly from those reported in [1]. Consequently, we utilized the correction equation $\beta = 1.006 \times 10^{-2} - 1.53 \times 10^{-4} P_c$ %/mmHg from our previous work, with the reference pressure P_{ref} set to 760 mmHg, which corresponds to the pressure at sea level. For the fixed station at Mawson, we used the correction factor $\beta = 0.9439$ %/mmHg, with the reference pressure P_{ref} set to 742.56 mmHg.

During the two-year period of Xue Long surveys, we encountered occasional gaps in the data collection due to technical difficulties. Specifically, we observed a significant decrease in count rates during DOY 325–328 (November 21–24, 2019) of the second survey year when the ship was docked at Zhongshan station to load cargo. We attributed this decrease to the instrument being covered by other cargo containers during the unloading. To avoid using contaminated data, we removed the affected data from further consideration.

Even after this removal, there is a clear discontinuity in the count rate, even though there is minimal change in solar modulation during the gap. We conclude that the shift occurred due to changes in the ship's configuration. During the 2019 survey year, the ship was heavily loaded during its journey to Antarctica but empty during its return to Shanghai. The Changvan was carried with the other containers, not separately, on an open deck. The implication of this normalization failure is that the yield function of the Changvan was significantly altered by the presence of the other containers on the southbound segment. We, therefore, have not used the southbound segment in further analysis.

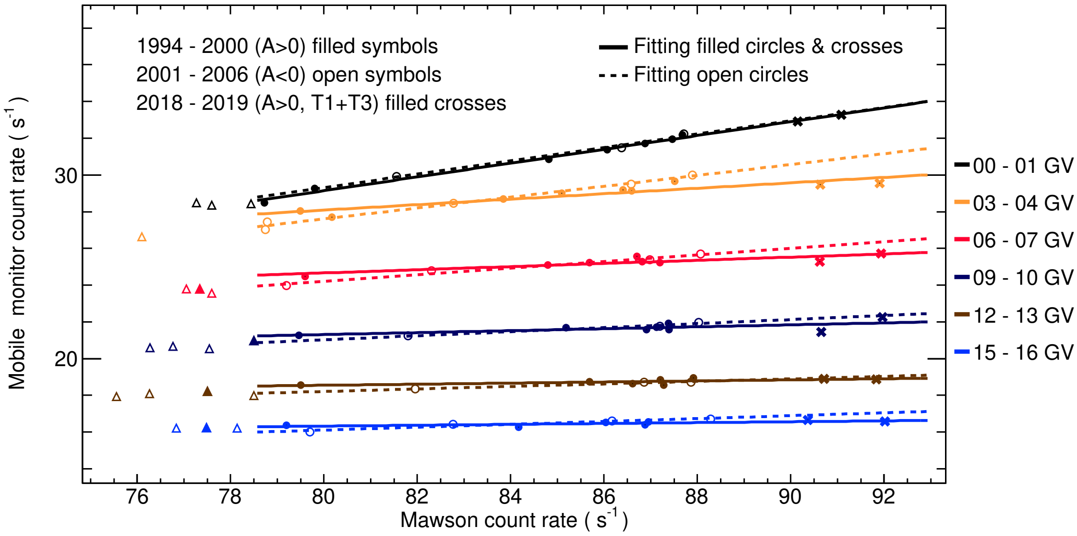

Figure 3: Regression of the mobile neutron monitor count rate in different apparent cutoff rigidity bins against the count rate of the Mawson neutron monitor. To improve clarity, we plotted every third bin. Filled circles indicate positive (A>0) solar magnetic polarity, while open circles indicate negative polarity. Lines are fit separately for positive and negative polarity. Triangles indicate times of uncertain polarity not included in the fits.

4. Linear Regression between Count Rates of Ship-Borne and Mawson Detectors

We studied data from 1994-2007 latitude surveys, previously analyzed by [1], and divided the count rate into 1 GV bin widths based on apparent cutoff rigidity. We plotted this against the Mawson neutron monitor count rate, as shown in Figure 3 (with every third rigidity bin). Our result can be compared with Figure 10 in [1]. The regression for each rigidity bin against Mawson can be fitted by a straight line. We confirm the change in the slope before and after the solar polarity reversal in the year 2000.

As there is no lead producer surrounding the central tube in these two surveys, we neglect data on this tube and use only the standard NM64s (T1&T3) flanking the central tube for the analysis. We normalized count rates of T1+T3 from the two most recent survey years to the previous survey year using factors of 1.824 and 1.795 for the survey years 2018 and 2019, respectively, and added them to the plot. The result from two recent survey years confirms linear trends and agreement with previous findings.

5. Spectrum Crossovers

In this work, the Dorman function is used to model the relationship between count rate and geomagnetic cutoff rigidity. The Levenberg-Marquardt algorithm is applied to minimize the least squares function and fit the Dorman function to the data. The Dorman parameters, N_0, α, κ, are 17.89, 6.07, and 0.766 for the survey year 2018 and 17.57, 7.64, and 0.840 for the survey year 2019.

Figure 4 displays the differential response functions for the two recent survey years, along with the previous results reported in [1]. Figure 4(a) shows the same spectral crossover revealed in Figure

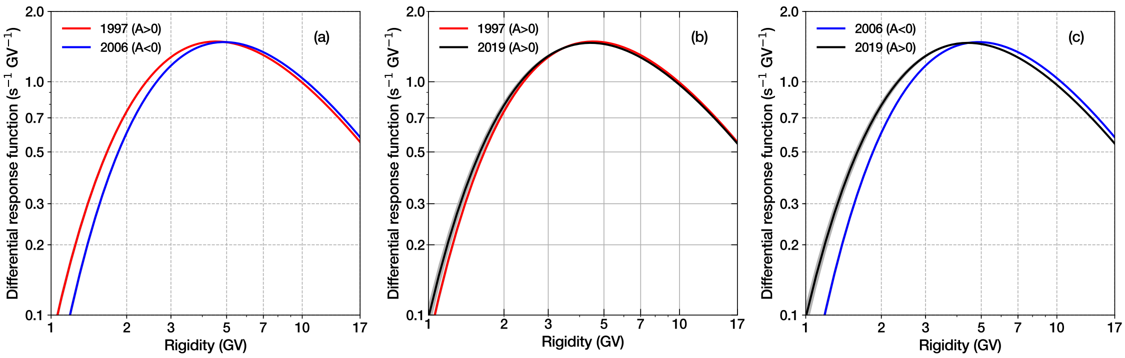

Figure 4: Differential response functions for survey years 2019 compared to earlier surveys performed near solar minima. Panel (a): The 1997 (red) and 2006 (blue) surveys, which had opposite solar magnetic polarity, show a crossover near 5 GV. Panel(b): The 1997 (red) and 2019 (black) surveys for T1 and T3, which had the same polarity, do not show a crossover. Panel (c): Results of the 2006 (blue) and 2019 (black) surveys, again with opposite polarity, show a crossover near 5 GV, similar to (a). The solid line represents the best-fit line, and the shaded area represents the possible range of fits ($\pm 2\sigma$).

8 of [1], with the addition of our newly updated results in Figure 4(b) and (c). The results show that the "crossover" in the spectra is clearly visible when the solar magnetic polarities are opposite, such as when there is a positive and negative magnetic polarity, as seen in Figures 4 (a) and (c). In contrast, there is no evidence of the "crossover" in the spectra when observing the same positive magnetic polarity, as shown in Figure 4 (b).

6. Discussion and Conclusions

Figure 4 displays the differential response functions for the two recent survey years, along with the previous results reported in [1]. To represent the scatter in the data, we also included statistical errors as an error band in Figure 4, although the bands appear as broad lines on the scale of the figure. The new results continue the historical pattern of spectral crossovers. The "crossover" in the spectra is clearly visible when the solar magnetic polarities are opposite. In contrast, there is no evidence of the "crossover" in the spectra when observing the same positive magnetic polarity.

The overall modulation level in the 2019 survey is less than that in the 1997 survey. This is seen mostly at lower rigidity, where the DRF for 2019 lies noticeably above that of 1997.

In addition to confirming the crossover, we showed that the linear analysis of the mobile monitor counting rates against the fixed station continues to have a slope that changes with solar magnetic polarity. The additional surveys support our previous proposal that different magnetic polarity effects are operating in solar modulation – drifts dominating at lower rigidity and helicity at higher rigidity.

7. Acknowledgements

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