PROCEEDINGS OF SCIENCE

Geomagnetic Storm Effects on the Solar Neutron Telescope at Sierra Negra, Mexico

J. Newton-Bosch,[a,*] L.X. González,[a,b] J.F. Valdés-Galicia,[a] O.G. Morales-Olivares,[c] Y. Muraki,[d] S. Shibata,[g] Y. Matsubara,[d] T. Sako,[e] K. Watanabe,[f] F. Monterde-Andrade,[a] S. Perea-Contreras,[a] E. Ortiz,[c] O. Musalem,[a] A. Hurtado[a] and R. Taylor[a]

[a] *Instituto de Geofísica, Universidad Nacional Autónoma de México, Circuito de la Investigación Científica, CDMX, 04510, Mexico*

[b] *LANCE/SCiESMEX, Instituto de Geofísica, Unidad Michoacán, Universidad Nacional Autónoma de México, Morelia, 58190, Michoacan, Mexico*

[c] *Escuela Nacional de Ciencias de la Tierra, Universidad Nacional Autónoma de México, Circuito de la Investigación Científica, CDMX, 04510, Mexico*

[d] *Institute for Space-Earth Environmental Research, Nagoya University, Furo-cho, Chikusa-ku, Nagoya, 464-8601, Japan*

[e] *Institute for Cosmic Ray Research, University of Tokyo, Kashiwanoha, Kashiwa, Chiba, 277-8582, Japan*

[f] *National Defense Academy of Japan, 1-10-20 Hashirimizu, Yokosuka, Kanagawa, 239-8686, Japan*

[g] *College of Engineering, Chubu University, Kasugai, 487-8501, Japan*

E-mail: jnewtonb@igeofisica.unam.mx, xavier@igeofisica.unam.mx

The effects of Space Weather events on cosmic rays detected by the Solar Neutron Telescope (SNT) at Sierra Negra, Mexico, were studied. The SNT is part of the Sierra Negra Cosmic Ray Observatory (SN-CRO), located at 4580 m a.s.l. We analyzed the data recorded by six SNT channels (C2, C3, C4, N2, N3, and N4) during geomagnetic storms from December 2015 to December 2022. Using the Dst and Kp indices, 30 moderate (Dst < -50 nT, Kp ≥ 5) and intense (Dst < -100 nT, Kp ≥ 7) geomagnetic storms were selected. The C2, C3, C4, N2, N3 and N4 channels detect charged and neutral particles, respectively, with energy deposition thresholds of E > 60, 90 and 120 MeV. The counting rates of these channels present diurnal variation, which was removed with the seasonal trend decomposition using Loess method. After data treatment, either significant decreases or enhancements were observed in the trend of at least one SNT channel for 21 of the analyzed events. Two confirmed Forbush decreases were also identified.

38th International Cosmic Ray Conference (ICRC 2023)
July 23rd-August 3rd, 2023
Nagoya, Japan

ICRC2023 38th International Cosmic Ray Conference The Astroparticle Physics Conference

*Speaker

https://pos.sissa.it/

PoS(ICRC2023)1272

1. Introduction

The phenomena that occurs in near-Earth space, modulated by the conditions of the Sun, the interplanetary medium, Earth's magnetosphere and upper atmosphere; as well as their impact on society and technology, is known as Space Weather (SW). Large disturbances in Space Weather, such as geomagnetic storms (GSs), shock waves and energetic particle events are mostly associated with three solar activity transient phenomena, also known as SW events: corotating interaction regions (CIRs), solar flares and coronal mass ejections (CMEs) [3].

A GS period is defined as a time interval during that a sufficiently intense and long-lasting interplanetary convection electric field leads, through a substantial energization in the magnetosphere-ionosphere system, to an intensified ring current strong enough to exceed some key threshold of the quantifying storm time Dst index [6].

Monitoring SW has gained relevance in recent decades, and Mexico has developed a Space Weather Service (SCiESMEX) since 2014. The SCiESMEX reports on past and real-time space weather events, publishing the data from several cosmic ray and radio telescopes across the country. Our research group includes the Solar Neutron Telescope (SNT) at Sierra Negra, located 4580 m a.s.l, which is able to detect galactic and solar cosmic rays (CRs).

Cosmic rays are affected by Space Weather in two ways: (a) intensity decreases caused generally by CMEs, and (b) intensity increases caused by the acceleration of particles in solar flares and/or in the interplanetary space [6].

The SNT consists of a 4 m^2 array of 30 cm thick plastic scintillators, surrounded by a gondola of anti-coincidence proportional counters, which allow the separation of signals from charged and neutral particles. In this way, the SNT has 4 energy deposition thresholds of E>30, 60, 90 and 120 MeV, which coincide with 8 main energy channels: 4 for charged particles (C1-C4) and 4 for neutral particles (N1-N4). For details in the SNT's structure and detection principles, see [4, 10, 11]. The objective of this study is to determine if the SNT could contribute to the SCiESMEX, establishing its signatures of SW events and its response to GSs.

2. Methodology

Based on the Dst and Kp indices, the occurrence of 25 moderate (Dst<-50 nT, Kp≥5) and 5 intense (Dst<-100 nT, Kp≥7) geomagnetic storms (GSs) was identified from December 2015 to December 2022. We had SNT data for 26 out of these 30 GSs. We analyzed the data registered by the SNT's N2-N4 and C2-C4 channels. The data were pressure corrected using the pressure correction coefficients calculated in [1]. Subsequently, the data were normalized to the average counting rate of four days prior to each GS. We also calculated the background data with a third degree polynomial curve.

The SNT channels have an exacerbated diurnal variation (DV), from ~ 2-12% of the counting rate. This DV was removed to verify if possible variations were indeed due to GSs. Each channel's counting rate was treated with a robust method of time series decomposition: the Seasonal-Trend decomposition using LOESS (STL) method. The STL method uses locally fitted regression models to decompose a time series into trend, seasonal, and remainder components. In this case, the seasonal component is the DV itself. So, we proceeded to analyze the trend of each channel's counting rate during GSs.

Two curves were compared: the background data and the data trend. We calculated significance lines above and below the background data curve based on each channel's DV percentage. In this way, for a 2% DV, another variation would have to be at least 50% of that DV to be significant. For 5% DV, the significance would be 35%, and for 8-12% DV, the significance would be 20%.

3. Results and Discussion

After data treatment, 21 SW events that produced GSs influenced the counting rate of at least one SNT channel. No variations were observed for three GSs, and the SNT data were incomplete or unreliable for the rest. The majority of GSs were caused by CIRs, given that we analyzed the descending phase of the 24th solar cycle, with minimal solar activity.

Significant increments, decrements and two confirmed Forbush decreases (July 16th and September 7th, 2017) were identified. The maximum percentage variations, shown in Table 1 for each event, was calculated relative to the background data. The results for the 21 events are shown in Table 1, including non-significant (NS) variations.

GS Date	SW Events	Dst, Kp Indices	N2 [%]	N3 [%]	N4 [%]	C2 [%]	C3 [%]	C4 [%]
20/12/15	2 CMEs	-155, 7	-3.35	-3.65	-3.73	-1.78	-2.12	-1.96
01/01/16	CME	-110, 6	-2.99	-2.76	-3.68	-2.08	-2.14	-3.10
20/01/16	CME	-93, 6	+1.06	+2.24	-2.30 (NS)	+1.73	+1.82	-4.30
18/02/16	CIR	-57, 6	-2.70	-2.94	-3.35	-1.61	-1.87	-1.86
06/03/16	2 CIRs	-98, 6	+5.83	+3.94	+11.45	+1.82	+1.93	+12.03
08/04/16	CIR	-60, 6	+1.08 (NS)	+1.58	+1.91 (NS)	+1.05 (NS)	+1.49	+1.13 (NS)
08/05/16	CIR	-88, 6	-1.80	-2.17	-2.81	-0.79 (NS)	-0.78 (NS)	-0.38 (NS)
29/10/16	CIR	-64, 6	-3.77 (NS)	-3.56	-3.81 (NS)	-0.43 (NS)	-0.42 (NS)	-1.18 (NS)
01/03/17	CIR	-61, 6	-4.47	-3.84	-4.12	-2.41	-1.82 (NS)	-2.23 (NS)
27/03/17	CIR	-74, 6	+0.72 (NS)	+0.70 (NS)	+1.01 (NS)	+1.25 (NS)	+1.60	+4.24 (NS)
28/05/17	CME	-125, 7	-1.13	-1.18 (NS)	-1.30	-0.63 (NS)	-0.83 (NS)	-0.51 (NS)
16/07/17	CME	-72, 6	-1.06	-1.18	-2.19	-1.09 (NS)	-1.43 (NS)	-2.28 (NS)
07/09/17	3 CMEs	-124, 8	-2.47	-2.71	-2.68	-1.63	-1.65	-1.29 (NS)
28/09/17	CIR	-55, 7	-1.29	-1.44	-2.08	-0.83 (NS)	-1.04 (NS)	-0.77 (NS)
20/04/18	CIR	-66, 6	+0.91 (NS)	+1.07	+2.41	+0.64 (NS)	+0.66 (NS)	+1.23 (NS)
06/05/18	CIR	-56, 6	+1.80 (NS)	+2.73	+3.68	+1.75	+2.23	+1.34 (NS)
05/11/18	CIR	-53, 6	+0.97 (NS)	+0.98 (NS)	+2.24	+0.37 (NS)	+0.34 (NS)	+0.23 (NS)
01/09/19	CIR	-52, 6	+1.23 (NS)	+0.79 (NS)	+3.34	+2.18	+1.97	+1.71 (NS)
12/10/21	CME	-57, 6	+1.16 (NS)	No data	No data	+2.23	No data	No data
04/11/21	CME	-105, 7	-2.24	No data	No data	-0.92 (NS)	No data	No data
04/09/22	CIR	-72, 6	-1.16	No data	No data	-1.15	No data	No data

Table 1: Geomagnetic Storms (GSs) with maximum percentage variations, including non-significant (NS) variations in SNT's main channels.

PoS(ICRC2023)1272

Most of the GSs produced decrements in the counting rate of at least one SNT channel, especially the ones caused by CMEs, supporting the fact that the magnetic structure of a CME acts as a barrier that diverts CRs that were Earth-bound. While the magnetic structure of CIRs differ, producing GSs that diminish the cutoff rigidity and allowing more particles to enter Earth's atmosphere. For detailed differences between CME and CIR-driven storms, see [2, 9].

Every SW event that we analyzed is unique, for example, the GSs that were driven by more than one SW perturbation had greater effects on the SNT channels, producing more intense variations. In this paper we will only describe the event of September 7th, 2017. Figures 1 and 2 show the graphs for this GS: the Dst index, and the neutral and charged particle channels of the SNT, respectively.

Between the days of September 4-10, 2017, multiple flares were observed on the Sun, with the X9.3 flare of September 6th being the most intense. At least three CMEs were observed along with these flares. The first one to interact with Earth's magnetosphere, on September 7th, produced a G4 GS. Almost a day later, the second CME arrived and on September 12th, the third one. Details on these SW events can be found in [5]. Figure 1 shows a Forbush decrease in the SNT's neutral particle channels that coincides with the Dst index minimum. After the decrease, the counting rates begin to increase, reaching a maximum that was barely significant in the most energetic N4 channel. Figure 2 also shows a Forbush decrease in the C2 and C3 channels, the C4 channel was not influenced by this GS.

The solar flare of September 10th, 2017, produced solar energetic particles (SEPs), with energies of 400 MeV, that induced the ground level enhancement (GLE) 72 [7, 8]. GLE 72 was observed by neutron monitors around the world and probably explains the increase shown in Figure 1.

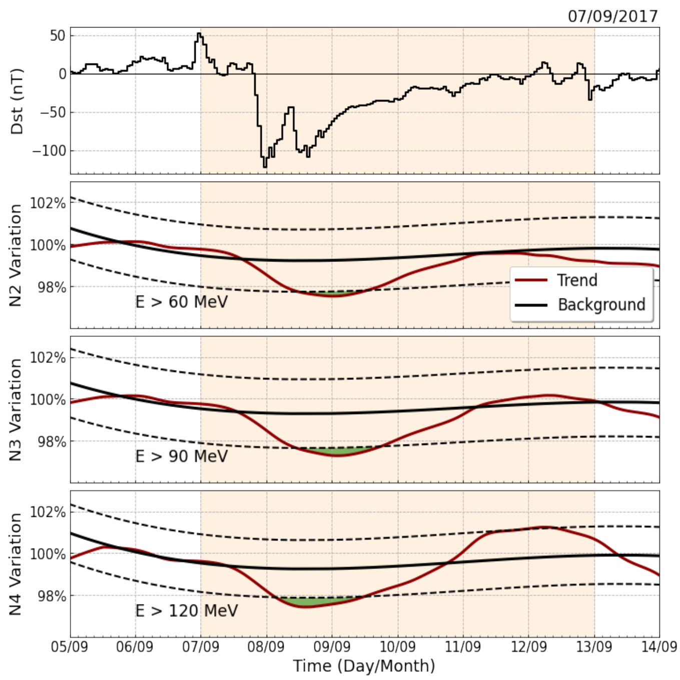

Figure 1: GS of September 7th 2017. The top panel shows the Dst index. The lower three panels show SNT's neutral particle channels percentage variations.

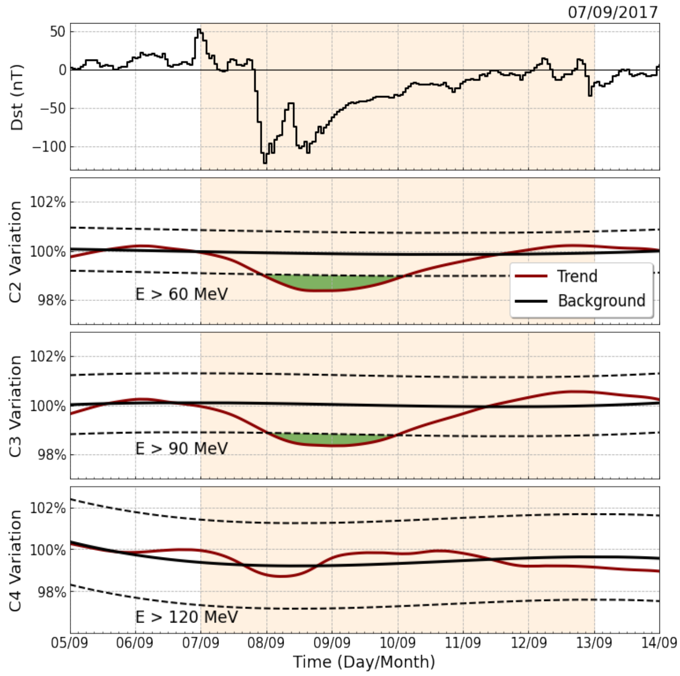

Figure 2: GS of September 7th 2017. The top panel shows the Dst index. The lower three panels show SNT's charged particle channels percentage variations.

4. Conclusions

- We detected that the measurements of CRs detected by the channels for neutral (N2, N3 and N4) and charged (C2, C3, C4) particles of the SNT present significant variations attributed to geomagnetic storms caused by CMEs and CIRs. In this way, it is confirmed that the SNT can be used to study variations in the CR flow attributed to geomagnetic storms. These variations were obtained by making a robust treatment of the data, finding its trend with the least possible contribution from the diurnal variation that each SNT channel presents.

- We observed that the events that presented variations in more than one channel show a greater disturbance as the energy threshold decreases, corroborating that the measurements are consistent.

- Our analysis shows that the signature of a CIR in the CRs detected by the SNT is generally a significant increase in the CR flux, which intensifies if a second SW event occurs. On the other hand, the signature of a CME is generally a decrease in the CR flux, whose significance is not a function of the intensity of the geomagnetic storm that it causes. These differences in CR effects between CME and CIR driven storms, might be explained with the magnetic structure of each SW event.

- Although there are many studies that have observed fluctuations in CRs attributed to SW perturbations, most obtain their measurements from satellites or detectors at mid-high latitudes. For this reason, the results of this work are of great relevance, since, where the SNT is located, the cutoff rigidity of 8.24 GV is relatively high. In addition, the SN-CRO is the second highest observatory in the world. With the results of this work, it is intended that the SNT be used as a tool for the analysis of Space Weather in Mexico.

References

[1] M. Barrantes, J. Valdés-Galicia, et al. Atmospheric corrections of the cosmic ray fluxes detected by the solar neutron telescope at the summit of the sierra negra volcano in mexico. *Geofísica internacional*, 57(4):253–275, 2018.

[2] J. E. Borovsky and M. H. Denton. Differences between cme-driven storms and cir-driven storms. *Journal of Geophysical Research: Space Physics*, 111(A7), 2006.

[3] E. Echer, W. Gonzalez, F. Guarnieri, A. Dal Lago, and L. Vieira. Introduction to space weather. *Advances in Space Research*, 35(5):855–865, 2005.

[4] L. X. González, F. Sánchez, and J. F. Valdés-Galicia. Geant4 simulation of the Solar Neutron Telescope at Sierra Negra, Mexico. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 613(2):263–271, 2010.

[5] J. Gonzalez-Esparza, M. Sergeeva, P. Corona-Romero, J. Mejia-Ambriz, L. Gonzalez, V. De la Luz, E. Aguilar-Rodriguez, M. Rodriguez, and E. Romero-Hernández. Space weather events, hurricanes, and earthquakes in mexico in september 2017. *Space Weather*, 16(12):2038–2051, 2018.

[6] K. Kudela, M. Storini, M. Y. Hofer, and A. Belov. Cosmic rays in relation to space weather. *Space Science Reviews*, 93(1-2):153, 2000.

[7] V. Kurt, A. Belov, K. Kudela, H. Mavromichalaki, L. Kashapova, B. Yushkov, and C. Sgouropoulos. Onset time of the gle 72 observed at neutron monitors and its relation to electromagnetic emissions. *Solar Physics*, 294:1–18, 2019.

[8] V. Kurt, A. Belov, K. Kudela, and B. Yushkov. Some characteristics of the gle on 10 september 2017. *arXiv preprint arXiv:1806.00226*, 2018.

[9] A. Pitňa, J. Šafránková, Z. Němeček, T. Ďurovcová, and A. Kis. Turbulence upstream and downstream of interplanetary shocks. *Frontiers in Physics*, 8:626768, 2021.

[10] J. F. Valdés-Galicia, A. Hurtado, O. Musalem, L. X. Gonzalez, Y. Muraki, Y. Matsubara, T. Sako, K. Watanabe, N. Hirano, N. Tateiwa, et al. A new solar neutron telescope in mexico. In *International Cosmic Ray Conference*, volume 6, page 3433, 2003.

[11] J. F. Valdés-Galicia, Y. Muraki, H. Tsujihara, T. Sako, O. Musalem, A. Hurtado, L. X. González, Y. Matsubara, K. Watanabe, N. Hirano, et al. An improved Solar Neutron Telescope installed at a very high altitude in Mexico. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, 535(3):656–664, 2004.