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Abstract

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Full Text

Testing the Effects of Cosmic Ray Flux Intensity Modulation on Solar Emission Characteristics

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Abstract

We investigate the relationship between the magnitudes of Forbush decreases (FDs) and solar-geomagnetic characteristics using daily-averaged galactic cosmic ray (GCR) data from Inuvik (INVK) and Magadan (MGDN) neutron monitor (NM) stations to quantify cases of GCR flux intensity modulation. The FDs were obtained with an automated computer software algorithm from daily-averaged GCR data from the IZMIRAN common website (http://cr0.izmiran.ru/common) at INVK (224 events) and MGDN (229 events) NM stations from 1998 to 2002. The associated solar-geomagnetic parameters for the same time range were obtained from the OMNI website. A statistical analytical method was employed to test the link between FD amplitudes and solar-geomagnetic variables. We observed negative trends in FD-IMF, FD-SWS, FD-Kp, FD-SSN, and FD-SI, while a positive relation was indicated in FD-Dst at both stations. All correlations are statistically significant at the 95% confidence level. These results imply that solar emission characteristics impact GCR flux intensity modulation.

Key words: methods: statistical – methods: data analysis – Sun: coronal mass ejections (CMEs) – (Sun:) solar-terrestrial relations – (Sun:) solar wind – (ISM:) cosmic rays

1. Introduction

Galactic cosmic rays (GCRs) are high-energy charged particles ranging from 100 MeV to 10 GeV (Adriani et al. 2009; Yu et al. 2015; Usoskin et al. 2020), composed of 2% electrons and 98% atomic nuclei, consisting of roughly 1% heavier nuclei, 12% helium, and 87% protons (Simpson 1983). GCRs originate within the Milky Way and move isotropically in the heliosphere, encountering a turbulent solar wind with an embedded heliospheric magnetic field. This leads to significant global and temporal variations in their intensity and energy as a function of position inside the heliosphere (Potgieter 2013). Periodic and abrupt GCR flux modulations result from solar wind interplanetary magnetic field (IMF) structures such as shocks, sheaths, coronal mass ejections/interplanetary coronal mass ejections (CMEs/ICMEs), and corotating interaction regions (e.g., Svensmark et al. 2012; Alhassan et al. 2022a). These modulations include periodic long-term variations such as diurnal anisotropies (Okike 2021a), 27-day, and 11-year cycles, as well as non-periodic short-term variabilities such as Forbush decreases (FD) and ground-level enhancements (Oh et al. 2008; Badruddin & Kumar 2015), which can be detected using ground-based neutron monitors (NMs) of the global network. The geomagnetic cutoff rigidity of a particular NM detector determines the magnitude of the depressions (Burger et al. 2000), representing the resistance cosmic ray particles encounter when penetrating Earth's magnetic field (Lingri et al. 2022).

When GCRs interact with transient disturbances from the Sun, they record significant information about incoming disturbances before they reach Earth.

These disturbances create unstable conditions in the magnetosphere, particularly those caused by solar flares, resulting in geomagnetic storms characterized by activity indices (e.g., Dst, Kp, and SI). These geomagnetic storms are frequently accompanied by FDs. First investigated by Scott Forbush approximately eight decades ago (Forbush 1937), FDs are transient phenomena describing short-term abrupt reductions in cosmic ray flux intensity, reaching optimum depressions in about a day and recovering gradually over several days (Forbush 1938; Lockwood 1971; Gopalswamy et al. 2014; Menteso et al. 2023). FDs can be categorized as recurrent or non-recurrent/sporadic based on the type of interplanetary medium that drives them. Recurrent FDs result from high-velocity streams originating from coronal holes that revolve around the Sun, while non-recurrent/sporadic FDs are caused by transient interplanetary events related to CMEs and their ICMEs flowing outward from the Sun (Cane 2000; Richardson 2004; Badruddin & Kumar 2015; Melkumyan et al. 2018; Menteso et al. 2023). Recurrent FDs exhibit symmetric profiles and low amplitudes compared to their non-recurrent counterparts, which show high magnitudes and asymmetric profiles (Lockwood 1971; Melkumyan et al. 2019).

Research on FD magnitudes observed by different ground-level NMs scattered globally remains a matter of interest (Belov et al. 2001; Okike & Collier 2011; Okike 2020a; Alhassan et al. 2022a). Events with magnitudes $ $3% are referred to as weak or small-amplitude FDs (Cane et al. 1993; Pudovkin & Veretenenko 1995; Oh et al. 2008; Okike 2021b), while those with magnitudes >3% are known as strong or large-amplitude FDs (Cane et al. 1993; Van Allen 1993; Belov 2008; Oh et al. 2008; Harrison & Ambaum 2010; Laken et al. 2012). The former result from lower solar wind speed (SWS) and weaker IMF intensity, while the latter are due to higher SWS and IMF strength (Belov et al. 2001; Oh et al. 2008). Badruddin et al. (1991) first investigated CR intensity depression at large-amplitude FDs resulting from shocks connected to helium enhancement, while those not connected with He shocks show relatively small depression in CR intensity. Kristjansson et al. (2008), Oh et al. (2008), Belov et al. (2001, 2014), and Okike (2021a) investigated CR intensity depressions and reported different results, ranging from -3% to -5%, attributing these variations to NM station thresholds and suggesting that FD strength relates to conditions of the solar wind plasma that originates them. Jamsen et al. (2007) and Lagoida et al. (2023) independently used FD catalogs and noted that the energy or rigidity of NMs plays a significant role in FD recovery time. Furthermore, Okike & Nwuzo (2020) argued that other factors might contribute to GCR intensity modulation at specific stations, using statistical methods of analysis.

CR intensity modulation can be well understood through correlation analysis between FDs and solar-geomagnetic characteristics. Recent literature provides good examples of this analysis (Kilpua et al. 2011; Mavromichalaki & Paouris 2012; Blanco et al. 2013; Mustajab & Badruddin 2013; Okike & Nwuzo 2020; Alhassan et al. 2021, 2022b; Menteso et al. 2023; Ugwu et al. 2024). Mavromichalaki & Paouris (2012) investigated GCR flux modulation and its effects on solar activity indices and heliospheric characteristics during solar cycles 23 and 24 using the CME-index. Kilpua et al. (2011) compared ICME properties during minima of solar cycles 22 and 23, suggesting that maximum magnetic fields of ICMEs during cycle 23 were about 30% lower with radial widths about 15% lower. Blanco et al. (2013) studied the effects of 59 shock-driving ICMEs on FDs discovered by the Oulu NM, reporting that only 25% were related to FDs >3%.

Despite these advances, literature searches reveal that little work has been done to understand the statistical relationship between FDs and solar-geomagnetic characteristics due to insufficient FD data. Previously, FDs were detected manually (Moraal et al. 2000a, 2000b; Shea & Smart 2000; Kristjansson et al. 2008; Oh et al. 2008; Lee et al. 2015), a method that is grueling and substandard for handling large datasets. While semi-automated techniques employed by Ramirez et al. (2013), Light et al. (2020), and the IZMIRAN team (Belov et al. 2018a, 2018b; Abunina et al. 2020) produced improvements, several potential pitfalls remain unaddressed. These methods lack sophisticated statistical approaches and adopt manual ways of single-event analysis, making it difficult to detect small-amplitude FDs and work with large-volume FD catalogs.

Recently, researchers (Ramirez et al. 2013; Okike 2019a, 2019b, 2020a, 2020b; Okike & Umahi 2019a; Light et al. 2020; Alhassan et al. 2022b) and the Pushkov Institute of Terrestrial Magnetism, Ionosphere, and Radio Wave Propagation (IZMIRAN) group have used automated methods for FD investigation. The IZMIRAN group developed catalogs of FDs, both large and very small, using the global survey method (GSM), which acquires CR data detected by all NMs installed worldwide. Alhassan et al. (2022b) developed a comprehensive list of FDs using an automated investigation method. This large volume of FD data (see Tables 2 and 3) obtained through the same automated approach enables critical statistical analysis.

In this work, we statistically investigate the effects of these FDs on solar-geomagnetic variables using data from Inuvik (INVK) and Magadan (MGDN) NM stations. Section 1 introduces the work, with data sources described in subsection 1.1. Section 2 discusses the methodology, while analysis, results, and discussion are presented in Section 3. Result validation appears in Section 4, and Section 5 summarizes and concludes the work.

1.1 Data Source

Daily-averaged CR data were obtained from the IZMIRAN common website between 1998 and 2002 (solar cycle 23) observed from INVK and MGDN NM stations. Their characteristics are presented in Table 1. Daily solar-geophysical parameters—IMF, SWS, and geomagnetic storm indices (Kp, SSN, Dst, and SI)—were downloaded from the OMNI database.

2. Methodology

Alhassan et al. (2022b) developed the R-based FD location code employed in this work. According to the authors, the R-code was created by Robert Gentleman and Ross Ihaka from the Department of Statistics, University of Auckland (R Foundation for Statistical Computing platform). They investigated FDs from three NM stations, including the two NMs used in the current work. The parameters of these stations are displayed in Table 1.

The two NM stations with different locations and rigidities (see Table 1) are expected to behave differently with respect to FD magnitude, number, and timing due to the significant impact of CR diurnal anisotropy (Ugwu et al. 2024). Alhassan et al. (2022b) employed a computer software algorithm for FD selection, which is adapted here without significant variation. This work accepts raw CR data as input, enabling development of large volumes of CR data. Depressions exhibited in time series CR data indicate FDs. For eight decades, researchers employed manual FD selection, involving visual identification of maximum depression points in plotted graphs, indicating onset phase and end time, and calculating each FD's amplitude (Alhassan et al. 2022b and references therein). Dumbovic et al. (2011) and Okike (2020c) noted this method is tedious and flawed.

Although semi-automated techniques employed by Ramirez et al. (2013), Light et al. (2020), and the IZMIRAN team (Belov et al. 2018a, 2018b; Abunina et al. 2020) improved upon manual methods, several potential pitfalls remain. These methods lack sophisticated statistical approaches and adopt manual single-event analysis, making it difficult to detect small-amplitude FDs and work with large-volume FD catalogs. The current work utilizes an automated method that overcomes manual technique challenges through its sensitivity, detecting all FD events with both large and small amplitudes. The large volume of FD catalogs presented in Tables 2 and 3 provides ample opportunity to study, for the first time, the statistical significance of FD events and solar-geomagnetic characteristics. Besides detecting accurate FDs with magnitude <0.01%, the code's measurements of event magnitude and timing are very apt and correct. The algorithm also addresses potential bias from problematic CR diurnal anisotropy.

3. Analysis, Results, and Discussion

This investigation employed two separate FD catalogs selected from INVK and MGDN NM stations. The FD counts are 224 and 229 respectively for INVK and MGDN (see Tables 2 and 3). The data contain both small and large FD events with amplitude ranges from -0.03% to -15.77%. The highest FD event was detected by MGDN on 2000 July 16, while the smallest was detected by INVK on 1999 August 25. The corresponding solar-geomagnetic parameters for the highest FD amplitude are IMF = 21.8, SWS = 816, Kp = 43, SSN = 283, Dst = -172, and SI = 226.1, while those for the smallest FD amplitude are

IMF = 7.7, SWS = 538, Kp = 20, SSN = 196, Dst = -15, and SI = 212.9. The columns in Tables 2 and 3 represent: S/N (serial number), Date (FD occurrence date), and solar-geomagnetic parameters in order of IMF, SWS, Kp, SSN, Dst, and SI, with the final column representing FD magnitude.

Okike (2019a, 2019b, 2020a, 2020c), Okike & Umahi (2019a, 2019b), Menteso et al. (2023), Alhassan et al. (2022b), and Ugwu et al. (2024) demonstrate that statistical arrangement of these data is possible with an R-algorithm using FD dates as input signals. Simultaneous FDs at the two stations were selected using a coincident algorithm, where simultaneous FDs refer to events observed at the same time by two or more NM stations. In this work, timing references the FD minimum point. Analysis of FDs with reference to the event's time of minimum reduction (Okike & Nwuzo 2020) is more precise than traditional timing based on onset point or main phase (Lockwood 1990; Tinsley & Deen 1991; Belov 2008; Oh et al. 2008, 2009; Kane 2010). While differences in timing of simultaneous FDs using onset or main phase at different locations may be significantly different or imprecise, Okike & Nwuzo (2020) clearly demonstrated that timing simultaneous FDs with reference to FD minimum is comparatively more accurate.

The coincident code developed by Okike (2021b), which identifies FD minimums occurring at the same hour or day across multiple CR detectors, is employed in this work. The selection accuracy of the implemented code (Okike & Menteso 2024) guarantees proper identification of simultaneous FDs. Differences in timing of simultaneous FD data with their associated solar-geomagnetic parameters are presented in Table 4.

Scatter plots and correlation analysis were used to ascertain the level of dependence between FD magnitude and solar-geomagnetic characteristics. The product-moment correlation coefficient is applied to determine the degree of statistical correlation according to Fisher (1915).

The scatter plots and correlation analysis for FD amplitude versus solar-geomagnetic parameters at INVK and MGDN are presented in Figures 1 and 2. Figure 3 displays the relationship between simultaneous FD amplitudes and corresponding solar-geomagnetic variables. Figure 1 shows dependence between FD amplitude and solar-geomagnetic parameters at INVK. Figure 1(a) shows FD amplitude is inversely related to IMF, with correlation coefficient r -0.33, R^2 0.11, and p-value of 3.23×10^{-7}. Figure 1(b) reveals a negative relationship between FD amplitudes and SWS, with r -0.27, R^2 0.07, and p-value of 2.72×10^{-5}. Figure 1(c) shows a negative relation in FD amplitude versus Kp, with r -0.24, R^2 0.05, and p-value of 0.01. Figure 1(d) indicates a negative relationship between FD amplitude and SSN, with r -0.26, R^2 0.06, and p-value of 0.012. Figure 1(e) shows FD amplitude is positively related to Dst, with r 0.39, R^2 0.15, and p-value of 1.80×10^{-9}. Figure 1(f) shows FD amplitude is inversely related to SI, with r -0.23, R^2 0.06, and p-value of 0.03. These results show statistically significant relations between FD amplitudes and solar-geomagnetic characteristics at INVK at the 95%

confidence level. Regression analysis results are presented in Table 5.

FD amplitudes versus solar-geomagnetic parameters at MGDN are displayed in Figure 2. Figure 2(a) shows a negative relationship in FD-IMF regression, with r -0.35, R^2 0.12, and p-value of 3.61×10^{-8}. The inverse relationship is also noted in FD-IMF regression at INVK, with a slightly higher trend at MGDN. Figure 2(b) reveals a negative trend for FD amplitude against SWS, with r -0.33, R^2 0.11, and p-value of 1.71×10^{-7}. Figure 2(c) shows a negative trend in FD amplitude against Kp, with r -0.25, R^2 0.06, and p-value of 0.02. Figure 2(d) shows an inverse relationship between FD amplitude and SSN, with r -0.25, R^2 0.06, and p-value of 0.01. Figure 2(e) shows a positive trend in FD amplitude versus Dst, with r 0.39, R^2 0.15, and p-value of 9.53×10^{-10}, similar to INVK results. The regression results for FD-SI displayed in Figure 2(f) indicate a negative trend, with r -0.22, R^2 0.05, and p-value of 0.06. Regression analyses using FD amplitudes and solar-geomagnetic variables at MGDN exhibit statistical significance at the 95% confidence level. A summary appears in Table 6.

We statistically analyzed relations between FD amplitudes and solar-geomagnetic characteristics at INVK and MGDN, finding significant correlation levels. These statistical significances indicate that solar-geomagnetic parameters link to CR intensity modulation (Belov et al. 2001; Richardson 2004; Mishra et al. 2005; Kane 2010; Dumbovic et al. 2011; Yu & Luo 2014; Okike 2020c; Alhassan et al. 2021; Fu et al. 2021a, 2021b; Menteso et al. 2023; Melkumyan et al. 2024; Ugwu et al. 2024).

We observed statistically significant correlations between FD amplitudes and IMF at both stations, with r -0.33 and -0.35 at INVK and MGDN respectively, providing evidence that IMF has greater effect on CR intensity modulation at MGDN compared to INVK. These results align with Ugwu et al. (2024) using FD-IMF analysis. Alhassan et al. (2021) and Dumbovic et al. (2011) revealed stronger trends with correlation coefficients of r -0.44 and -0.62 respectively in FD-IMF relations compared to the present result. The weaker correlation in the current work is expected since the FD catalogs contain small-amplitude FDs, supporting the assertion that weak FDs might result from CME or ICME interactions with Earth's magnetic field.

A stronger trend in FD-SWS relation appears at MGDN (r -0.33) compared to INVK (r -0.27). These results align with Singh & Badruddin (2007), Bhaskar et al. (2016), and Ugwu et al. (2024), but contrast with Menteso et al. (2023) and Alhassan et al. (2021). Menteso et al. (2023) reported lower results (r -0.1 and -0.03) for the two stations they studied, while Alhassan et al. (2021) revealed higher results (r -0.44) compared to the present work. These results obviously support that SWS impacts CR intensity variation.

Statistically significant correlations exist in FD-Kp, FD-SSN, FD-Dst, and FD-SI at both stations, with inverse correlations for FD-Kp, FD-SSN, and FD-SI, and direct correlation for FD-Dt at both stations. These trends in FD amplitudes and geomagnetic index relations emphasize that these variables might influence solar activities (Richardson 2004; Mishra et al. 2005; Kane 2010; Singh & Bhargawa 2020; Fu et al. 2021a, 2021b; Kumar et al. 2023; Melkumyan et al. 2024). Differences observed at different NM stations (INVK and MGDN) might result from station characteristics such as rigidity cutoff and/or CR diurnal anisotropy. Large data volumes are recommended to confirm this claim. The reported relations between FD amplitude and solar-geomagnetic characteristics, with 95% statistical significance, agree with other literature reports.

4. Result Validation

Due to difficulties in detecting, timing, and accurately determining FD events (Ramirez et al. 2013), validation of every new FD datum is necessary. The first step taken was the correlation test discussed above. Events were also compared (not shown here) with one of the largest FD catalogs developed by the IZMIRAN group within the same time lag. However, literature indicates difficulties in uniting two FD catalogs calculated by different methods (Abunin et al. 2013). This was obvious in Figure 9 of Menteso et al. (2023), where their software measured the event's minimum reduction time while the IZMIRAN GSM determined onset time. Furthermore, Okike (2021a) illustrated implications of using different baselines in determining FD events, stating significant differences between IZMIRAN catalogs and others.

To meet the reliable validation target set by Abunin et al. (2013), two FD catalogs at INVK and MGDN selected using the same method were employed. The total FD counts selected from INVK and MGDN stations were 224 and 229 respectively. Simultaneous FDs at the two stations numbered 138 (see Table 4). The scatter plot of simultaneous FDs at INVK and MGDN versus solar parameters appears in Figure 3, while the scatter plot of simultaneous FDs at INVK against MGDN appears in Figure 4. Simultaneous FD data show statistically significant relations with solar variables (IMF, SWS, Kp, SSN, Dst, and SI) with correlation coefficients of r -0.33, -0.39, -0.24, -0.27, 0.41, and -0.24 respectively for IMF, SWS, Kp, SSN, Dst, and SI at INVK. Simultaneous FD versus solar variables at MGDN shows noticeably higher trends than INVK (except in Dst where the relation is lower at MGDN) with correlation coefficients of r -0.34, -0.40, -0.25, -0.30, 0.39, and -0.25 respectively for IMF, SWS, Kp, SSN, Dst, and SI (see Table 7). These differences can be attributed to different station characteristics (see Table 1).

A statistically significant relation exists between simultaneous FDs at INVK and MGDN with correlation coefficient r 0.97 and coefficient of determination R^2 0.93. These results imply that 93% of simultaneous FD variation may be attributed to the same global events (Cane 2000; Oh et al. 2009; Lee et al. 2015). Remaining non-simultaneous FDs may result from different NM station characteristics and CR diurnal anisotropy that varies significantly over Earth. Wibberenz et al. (1998), Cane & Richardson (2003), Jordan et al. (2011), and Okike & Nwuzo (2020) noted that time variations and phase shifts in non-simultaneous

FDs can be attributed to location-dependent and diurnal anisotropy of CRs. Alhassan et al. (2022b) illustrated these time variations in non-simultaneous FD events. Menteso et al. (2023) indicated in Figure 8 that non-simultaneous FD events were more obvious in high-amplitude FDs, suggesting solar cycle effects contributed to differences. These patterns are reflected in the current work as shown in Tables 1, 2, and 3 and Figures 3 and 4.

The relation between FDs regarding timing and magnitude has often been described using isolated events. For example, Figures 2 and 3 of Oh et al. (2008) and Figures 1 and 2 of Okike & Collier (2011) graphically illustrated simultaneous and non-simultaneous FDs. While these case studies are interesting, statistical/quantitative representations are lacking in literature. Table 1 of Oh et al. (2008) presents magnitudes of 49 FDs (simultaneous and non-simultaneous) at Oulu station, but magnitudes and timing for the remaining two stations (INVK and MGDN) are not presented, leaving readers to speculate. Oh et al. (2008) concluded that high-amplitude FDs tend to be observed globally whereas small-amplitude events are non-simultaneous.

Here we present statistical illustration of variation patterns for both simultaneous and non-simultaneous FDs. Figure 5 allows assessment of differences and similarities in magnitude and timing. While Figure 4 does not allow comparison of event magnitudes, panel (a) of Figure 5 shows CR intensity variation is significant and unpredictable at INVK and MGDN. Differences in magnitudes of some simultaneous FD pairs are visually evident. For instance, the first two pairs suggest MGDN measures larger intensity variation during the FD event of 2000 July 16, but a different scenario appears for the next event pair (2001 April 12), where INVK measures higher intensity variation. Some cases show insignificant magnitude differences between stations. These uncertain patterns query the expectation that stations with lower rigidity (INVK GV = 0.17 GV) should see higher intensity variation than MGDN with higher rigidity (MGDN GV = 1.99 GV) (Okike 2020c).

Comparison of panels (a) and (b) in Figure 5 is also revealing. While some trend is observable in panel (a), no pattern is evident in panel (b). Globally simultaneous FDs may relate to common solar causative agents, but such association is difficult for non-simultaneous FDs where event forms/numbers/magnitudes vary appreciably between locations. This explains significantly different scattered data points in panel (b). Perfect vertical alignments in panel (a) allow visual matching, but matching is difficult in panel (b). Non-simultaneous FDs may result from complex local CR phenomena (e.g., CR anisotropy and solar cycle oscillation). Simultaneous FDs are, on average, larger than non-simultaneous FDs as suggested by the horizontal line (Oh et al. 2008). Mean variations for simultaneous FDs at INVK and MGDN are 4.5% and 4.3% respectively. For non-simultaneous FDs, mean event magnitudes are 3.3% and 3.0% respectively. Black horizontal lines represent FD magnitude = -3%. Non-simultaneous FD counts are 86 at INVK and 91 at MGDN.

5. Summary and Conclusion

The proposed link between GCR flux intensity and solar emission characteristics has been investigated. The interrelationships have been a significant challenge in astrophysics. Traditional manual selection methods of depressions in GCR count rates have hindered researchers, especially when considering catalogs with small/weak FD amplitudes. This bias was addressed by recent work (Okike & Alhassan 2021; Okike et al. 2021; Alhassan et al. 2022b). In this work, we employed automated FD selection from INVK and MGDN NM stations from 1998 to 2002. Associated solar-geomagnetic parameters were generated using computer algorithm-software code. Data analyses revealed negative trends in FD-IMF, FD-SWS, FD-Kp, FD-SSN, and FD-SI at both individual and simultaneous levels. Positive relations in FD-Dst were noted at both stations individually and simultaneously. Results indicate statistically significant correlations with r -0.33, -0.27, -0.24, -0.26, 0.39, and -0.23 respectively for FD-IMF, FD-SWS, FD-Kp, FD-SSN, FD-Dst, and FD-SI at INVK, and r -0.35, -0.33, -0.25, -0.25, 0.39, and -0.22 at MGDN. Coherent FD-Dst results appear in both stations, while differences in other parameters could result from different NM characteristics, though FD-Dst appears less affected. These inconsistencies strongly call for further investigation.

A critical examination of Table 4 shows that all weak/small-amplitude FDs are non-simultaneous at different NM stations (see Tables 8 and 9 of Menteso et al. 2023), indicating minimal possibility of detecting simultaneous weak/small-amplitude FDs at two different NM stations. More obvious relationships appear in FD-solar-terrestrial parameters for simultaneous FDs compared to non-simultaneous ones, warranting further investigation. These results imply that solar emission characteristics are key drivers of GCR flux intensity modulations. We conclude that GCR intensity modulation could be attributed to solar-geomagnetic parameters, but emphasize the importance of repeating this analysis using Fourier-decomposed GCR data that accounts for CR anisotropy influence, which will be the target of future research.

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References

Abunin, A., Abunina, M. A., Belov, A. V., et al. 2013, JPhCS, 409, 012165 Abunina, M. A., Belov, A. V., Eronshenko, E. A., et al. 2020, SoPh, 295, 7 Adriani, O., Barbarino, G., Bazilevskaya, G., et al. 2009, Natur, 458, 607 Alhassan, J. A., Okike, O., & Chukwude, A. E. 2021, RAA, 21, 1 Alhassan, J. A., Okike, O., & Chukwude, A. E. 2022a, RAA, 22, 055014 Alhassan, J. A., Okike, O., & Chukwude, A. E. 2022b, JApA, 43, 1 Badruddin, B., Venkatesan, D., & Ananth, G. 1991, SoPh, 134, 395 Badruddin, & Kumar, A. 2015, SoPh, 290, 1271 Belov, A., Abunin, A., Abunina, M., et al. 2014, SoPh, 289, 3949 Belov, A., Eroshenko, E., Yanke, V., et al. 2018a, SoPh, 293, 68 Belov, A. V. 2008, in IAU Symp. 257, Universal Heliophysical Processes, ed. N. Gopalswamy & D. F. Webb (Cambridge: Cambridge Univ. Press) Belov, A. V., Eroshenko, E. A., Oleneva, V. A., Struminsky, A. B., & Yanke, V. G. 2001, AdSpR, 27, 625 Belov, A. V., Eroshenko, E. A., Yanke, V. G., et al. 2018b, Ge&Ae, 58, 356 Bhaskar, A., Vichare, G., Arunbabu, K. P., & Raghav, A. 2016, Ap&SS, 361, 242 Blanco, J., Catalán, E., Hidalgo, M.A., et al. 2013, Soph, 284, 167 Burger, R., Potgieter, M., & Heber, B. 2000, JGR, 105, 27447 Cane, H. V. 2000, SSRv, 93, 55 Cane, H. V., & Richardson, I. G. 2003, JGR, 108, 1156 Cane, H. V., Richardson, I. G., & von Rosenvinge, T. T. 1993, JGR, 98, 295 Cane, H. V., Richardson, I. G., & von Rosenvinge, T. T. 1996, JGR, 101, Dumbovic, M., Vrsnak, B., Calogovic, J., & Karlica, M. 2011, A&A, 531, 1 Fisher, R. 1915, Biometrika, 10, 507 Forbush, S. E. 1937, PhRv, 51, 1108 Forbush, S. E. 1938, PhRv, 54, 975 Fu, S., Zhang, X., Zhao, L., & Li, Y. 2021a, ApJS, 254, 37 Fu, S., Zhang, X., Zhao, L., & Li, Y. 2021b, ApJL, 920, L12 Gopalswamy, N., Akiyama, S., Yashiro, S., et al. 2014, GeoRL, 41, 2673 Harrison, R., & Ambaum, M. 2010, JASTP, 72, 1408 Jamsen, T., Usoskin, I. G., Raiha, T., Sarkamo, J., & Kovaltsov, G. 2007, AdSpR, 40, 342 Jordan, A. P., Spence, H. E., Blake, J. B., & Shaul, D. N. A. 2011, JGRA, 116, A11103 Kane, R. P. 2010, AnGeo, 28, 479 Kilpua, E. K. J., Lee, C.O., Luhmann, J.G., & Li, Y. 2011, AnGeo, 29, 1455 Kristjansson, J. E., Stjern, C., Stordal, F., et al. 2008, ACPD, 8, 13265 Kumar, V., Dhaka, S. K., Hitchman, M. H., & Yoden, S. 2023, NatSR, 13, 3707 Lagoida, I., Voronov, S., Mikhailov, V., et al. 2023, SoPh, 298, 9 Laken, B. A., Palle, E., Calogovic, J., & Dunne, E. 2012, JSWSC, 2, A185 Lee, S., Oh, S., Yi, Y., et al. 2015, JASS, 32, 33 Light, C., Bindi, V., Consolandi, C., et al. 2020, ApJ, 896, 133 Lingri, D., Mavromichalaki, H., Belov, A., et al. 2022, SoPh, 297, 24 Lockwood, J. A. 1971, SSRv, 12, 658 Lockwood, J. A. 1990, Solar Geophys Data, 549, 163 Mavromichalaki, H., & Paouris, E. 2012, AdAst, 2012, 607172 Melkumyan, A. A., Belov, A. V., Abunina, M. A., et al. 2018, Ge&Ae, 58, 154 Melkumyan, A. A., Belov, A. V., Abunina, M. A., et al. 2019, STP, 5, 28 Melkumyan, A. A., Belov, A. V., Abunina, M. A., et al. 2024, SoPh, 299, 40 Menteso, F., Chukwude, A., Okike, O., & Alhassan, J. 2023, MNRAS, 521, 6330 Mishra, S. K., Tiwari, D. P., & Kaushik, S. C. 2005, IJMPA, 20, 6717 Moraal, H., Belov, A., & Clem, J. M. 2000a, JGR, 93, 263 Moraal, H., Belove, A., & Clem, J. M. 2000b, SSRv, 93, 263 Mustajab, F., & Badruddin 2013, P&SS, 82, 43 Oh, S., Yi, Y., & Kim, H. Y. 2008, JGRA, 113, A01103 Oh, S., Yi, Y., & Kim, H. Y. 2009, JGRA, 114, A11102 Okike, O. 2019a, ApJ, 882, 1 Okike, O. 2019b, JGRA, 124, 3910 Okike, O. 2020a, MNRAS, 491, 3793 Okike, O. 2020b, DIB, 33, 106463 Okike, O. 2020c, JASTP, 211, 1364 Okike, O. 2021a, ApJ, 915, 60 Okike, O. 2021b, ApJ, 503, 60 Okike, O., & Alhassan, J. A. 2021, SoPh, 296, 21 Okike, O., & Collier, A. B. 2011, JASTP, 73, 796 Okike, O., & Menteso, F. M. 2024, RASTI, 3, 853 Okike, O., & Nwuzo, O. C. 2020, MNRAS, 493, 1948 Okike, O., Nwuzor, O., Odo, F., et al. 2021, MNRAS, 502, 300 Okike, O., &

Umahi, A. E. 2019a, JASTP, 189, 35 Okike, O., & Umahi, A. E. 2019b, SoPh, 294, 16 Potgieter, M. S. 2013, LRSP, 10, 3 Pudovkin, M. I., & Veretenenko, S. V. 1995, JATP, 57, 1349 Ramirez, O. O. U., Galicia, J. F. V., Munoz, G., & Huttunen, E. 2013, 33rd ICRC (Rio de Janeiro), 1, 1967 Richardson, I. G. 2004, SSRv, 111, 267 Richardson, I. G., & Cane, H. V. 2011, SoPh, 8, 609 Shea, M. A., & Smart, D. F. 2000, SSRv, 93, 229 Simpson, J. A. 1983, ARNPS, 33, 323 Singh, A. K., & Bhargawa, A. 2020, AdSpR, 65, 1831 Singh, Y. P., & Badruddin 2007, JGR, 112, 581 Svensmark, J., Enghoff, M. B., & Svensmark, H. 2012, ACPD, 12, 3595 Tinsley, B. A., & Deen, G. W. 1991, JGR, 96, 22283 Ugwu, C. J., Okike, O., Menteso, F. W., et al. 2024, Ap&SS, 369, 45 Usoskin, I., Koldobskiy, S., Kovaltsov, G. A., et al. 2020, A&A, 640, Van Allen, J. 1993, GeoRL, 20, 2797 Wibberenz, G., Le Roux, J. A., Potgieter, M., & Bieber, J. 1998, SSRv, 83, 309 Yu, F., & Luo, G. 2014, ERL, 9, 045004 Yu, X. X., Lu, H., Chen, G. T., et al. 2015, NewA, 39, 25

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