THE INFLUENCE OF SOLAR CORONAL MASS EJECTIONS AND INTERPLANETARY MAGNETIC FIELDS ON FORBUSH DECREASES IN COSMIC RAY INTENSITY DURING SOLAR CYCLE 24

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Abstract

We studied the Forbush decreases of cosmic rays intensity during the Solar Cycle 24 using the Moscow Neutron Monitor. Forbush decreases (FDs) are sudden, short-term reductions in cosmic ray intensity observed on Earth, commonly triggered by solar events such as Coronal Mass Ejections (CMEs), solar flare (SFs) and Interplanetary Magnetic Fields (IMFs). We will explore the effects of major causes of Forbush decreases such as solar coronal mass injection, solar flares and Interplanetary Magnetic Field (IMF) to understand how the Fds in cosmic ray intensity are caused by them. This paper explores the effect of solar CME, SF and IMF on Forbush decreases as well as their interaction and investigates the underlying mechanisms responsible for the modulation of cosmic ray intensity during these events.In this study report, we have gathered a total of 56 Forbush decreases of magnitude ≥3% from the Moscow Neutron Monitor during Solar Cycle 24. This study uses observational data from Moscow neutron monitors, Omniweb, National Oceanic and Atmospheric Administration (NOAA) and the Solar and Heliospheric Observatory (SOHO) to examine how the IMF, solar flares, and CMEs impact FDs during SC 24. 94% of Fds are linked to solar flares, and the majorities are linked to halo CME and partial halo CME, according to our observations. The magnitude of Fds and the speed of CME were shown to be positively correlated, with a coefficient of 0.28. Also, all the Forbush decreases are associated with IMF. We observe a positive correlation between the magnitude of Fds and the peak value of IMF, with a correlation coefficient of 0.24. We found a positive correlation between the magnitude of Fds and the magnitude of IMF, with a correlation coefficient of 0.25. We concluded that the CME associated with IMF and SF are responsible for the Forbush decreases.

Keyword: - Forbush decreases (Fds), Coronal Mass Ejections (CMEs), Interplanetary magnetic fields (IMF), Solar Flare (SF), Solar Cycle (SC), Cosmic Rays (CR)

1. Introduction

High energy particles called cosmic rays are mostly made up of protons, heavy nuclei, and trace amounts of electrons. Our galaxy and other galaxies outside of the solar system are the sources of these cosmic rays, in addition to the sun. These cosmic rays travel towards the earth, but the intensity of CR is controlled by solar variables. Particularly during the occurrence of SFs and CME, it affects the intensity of CRs, which results in Forbush decreases. These Fds are typically abrupt and transient drops in CR intensity. SC 24 began in December 2008 and ended in December 2019 with the lowest solar activity. Compared to the previous solar cycle, there was less solar activity during this one. However, solar cycle 24 still had several significant CME, which affected the intensity of cosmic rays. The intensity of CR is influenced by magnetic fields produced by solar flares, the IMF, and the SW. Large changes in the heliosphere's magnetic field can be caused by coronal mass ejections (CMEs), which are magnetized structures that change the heliosphere's circumstances. During periods of strong solar activity, CMEs moving at different speeds frequently combine to form complex ejecta, which are frequently observed in the interplanetary medium. The solar wind's IMF is essential for regulating cosmic rays, and its behavior during this cycle offers valuable information about the connection between solar activity and CR intensity (Verma et al., 2014).

Several researchers have studied Forbush decreases in CR intensity with solar activity variables, CMEs and related interplanetary phenomena, and concluded that CMEs and interplanetary shocks are possible causes of cosmic ray decay (Zhang, G. et al. 1988, 2004). Cane H.V. (2000) determined that coronal mass ejections (CMEs) are large-scale occurrences that alter the interplanetary magnetic field's (IMF) configuration and obviously affect the cosmic ray strength for a brief period of time. Additionally, Manoharan et al. [2004] found a strong relationship between interplanetary CME and solar activity parameters, as well as between interplanetary shocks and fluctuations in cosmic ray intensity. Badruddin and Y P Singh (2003) investigated how solar flares, related interplanetary magnetic fields, and radio bursts can cause short-term drops in CRs intensity. The majority of flares linked to increases in solar wind speed and IMF intensity are also linked to type IV ray occurrences and large-amplitude short-period cosmic ray decreases. Chertok et al. (2013) studied the connections among the parameters of SFs and the features of FDs brought on by CMEs from the solar disk's central zone during sc 23. They came to the conclusion that solar radiation factors play a major role in determining the primary quantitative characteristics of the primary non-repetitive FDs. Hubert G. et al (2019) studied Forbes decreases with various solar and interplanetary parameters and concluded that CMEs and their interplanetary manifestations have a significant correlation with these declines.

The behavior of Forbush declines is significantly influenced by the IMF. The IMF, which is generated by the Sun's magnetic field, can scatter cosmic rays, which makes it more difficult for them to reach Earth. The IMF's structure changed during SC 24 as a result of the Sun's magnetic field going into reverse phase. This could have helped explain the observed Forbush decreases, especially in relation to CMEs and high-speed solar wind. During a CME event, the IMF configuration usually consists of a very turbulent and compressed area that can help lessen the observed intensity on Earth by scattering and deflecting cosmic rays. During FDs, the intensity and orientation of the IMF are crucial in determining how much cosmic ray flux is modulated. This research paper explores the role of CMEs, IMF and solar flare in causing FDs during solar cycle 24, analyzing their effects on cosmic ray intensity, and providing a detailed examination of the mechanisms responsible for these decreases.

2. Data Reduction and Analysis

In this research paper, we have collected a total of 56 Forbush decreases of magnitude ≥3 from the Moscow Neutron Monitor during Solar Cycle 24. This research examines Fds in CR intensity in relation to various solar phenomena, SFs, IMFs, and CMEs. The analysis utilized hourly count rate data from the Moscow neutron monitors covering the duration of solar cycle 24. Data from extreme ultraviolet imaging telescopes (EIT) and large angle spectrometric coronagraphs (SOHO/LASCO) are used to determine the various forms of CMEs. These data have been collected from the Omni Web and used to determine the interplanetary magnetic field (http://omniweb.gsfc.nasa.gov/form/dxi.html). The data of X-ray solar flares and other solar data, solar geophysical data report U.S. Department of commerce, NOAA monthly issue and solar STP data (http://www.ngdc.noaa.gov/stp/solar/solardataservices.html.) have been used. In this investigation Forbush decreases (Fds) has been analyzed with CMEs and IMF and solar features associated interplanetary parameters such as, solar flares, over the period of solar cycle 24.

Table- Association with Fds with CMEs, IMF and Solar Flare

S. No.	Date	Forbush Decreases		IMF		CME		Solar flare
		Onsert Time DD(HH)	Fds Magnitude (%)	Onsert Time DD(HH)	Magnitude (nT)	Type of CME	Speed of CME Km/S	class of flares
1	05/04/2010	05 (09)	3	04(08)	14	Halo	668	B-74
2	28/05/2010	28 (12)	3	27(15)	12	NA	NA	B-14
3	31/10/2010	31(09)	3	31(02)	9	Partial Halo	357	B-20
4	18/02/2011	18(00)	4	17(13)	28	Halo	669	X-22
5	10/03/2011	10(20)	3	09(20)	7	Partial Halo	732	M-15
6	29/03/2011	29(14)	4	28(22)	12	Halo	1066	C-10
7	06/04/2011	06(05)	3	05(09)	12	NA	NA	B-74
8	07/04/2011	07(08)	3	06(09)	9	NA	NA	C-12
9	04/06/2011	04(18)	4	03(22)	21	Halo	999	C-37
10	10/06/2011	10(10)	3	09(11)	6	Halo	1258	M-25
11	23/06/2011	23(00)	3	22(01)	7	Halo	719	C-77
12	05/08/2011	05(06)	5	04(06)	26	Partial Halo	712	M-14
13	26/09/2011	26(10)	4	25(10)	30	Halo	2254	X-19
14	24/10/2011	24(13)	5	23(17)	22	Halo	1164	M-13
15	24/01/2012	24(08)	4	23(19)	11	NA	NA	M-87
16	31/01/2012	31(11)	3	30(09)	8	Halo	3090	X-17
17	21/02/2012	21(22)	3	21(02)	6	Partial Halo	539	C-10
18	06/03/2012	06(07)	3	05(07)	7	Halo	1473	M-20
19	07/03/2012	07(10)	12	06(17)	14	Halo	1531	X-11
20	05/04/2012	05(07)	4	04(12)	8	Partial Halo	452	B-79
21	16/06/2012	16(08)	5	16(08)	37	Halo	987	M-19
22	04/07/2012	04(12)	4	03(13)	6	Halo	1074	M-56
23	14/07/2012	14(17)	6	13(19)	24	Halo	2265	X-14
24	19/07/2012	19(14)	4	18(08)	4	Partial Halo	1511	M-17
25	04/09/2012	04(08)	4	03(11)	13	Halo	538	C-29
26	08/10/2012	08(12)	4	07(09)	11	Partial Halo	885	B-78
27	13/11/2012	13(09)	4	12(13)	19	Partial Halo	1039	NA
28	14/04/2013	14(08)	5	13(12)	9	NA	NA	C-14
29	23/06/2013	23(08)	5	22(13)	3	Partial Halo	1907	M-29
30	14/12/2013	14(17)	3	13(12)	11	Partial Halo	1002	C-46
31	15/12/2013	15(09)	4	14(18)	4	Halo	1402	C-34
32	09/01/2014	09(13)	3	08(10)	9	Halo	1830	X-12
33	11/02/2014	11(08)	3	11(06)	5	Halo	908	M-10
34	15/02/2014	15(12)	4	14(14)	12	Halo	960	M-21
35	20/02/2014	20(11)	4	19(12)	5	Halo	779	C-47
36	28/02/2014	28(10)	4	27(08)	12	Halo	2147	X-49
37	18/04/2014	18(10)	4	17(10)	3	Partial Halo	583	C-73
38	07/06/2014	07(15)	4	06(16)	10	Halo	1258	C-13
39	12/09/2014	12(08)	5	11(19)	27	Halo	1267	X-16
40	21/12/2014	21(11)	8	21(01)	20	Halo	1331	X-18

41	16/03/2015	16(20)	4	15(22)	27	Halo	719	M-12
42	20/06/2015	20(12)	9	19(08)	2	Halo	1477	M-38
43	13/07/2015	13(00)	3	12(03)	6	Partial Halo	525	C-12
44	31/12/2015	31(13)	4	30(10)	13	Halo	1243	M-18
45	01/02/2016	01(10)	3	30(22)	6	Partial Halo	514	C-12
46	03/02/2016	03(08)	4	02(11)	5	Partial Halo	540	C-16
47	12/02/2016	12(09)	3	11(00)	15	NA	NA	C-26
48	26/02/2016	26(07)	3	25(05)	7	NA	NA	B-32
49	23/03/2016	23(09)	3	22(11)	6	NA	NA	NA
50	20/07/2016	20(11)	3	19(16)	24	Halo	405	C-14
51	17/09/2016	17(11)	3	16(12)	3	Partial Halo	742	B-19
52	14/10/2016	14(14)	3	13(04)	20	NA	NA	B-89
53	04/04/2017	04(06)	3	04(00)	14	NA	NA	M-58
54	16/07/2017	16(04)	6	15(16)	21	Halo	1200	M-20
55	07/09/2017	07(20)	8	06(20)	25	Halo	1636	M-10
56	21/09/2018	21(05)	4	21(02)	8	NA	NA	NA

3. Data Analysis and Results

3.1 Solar Coronal Mass Ejections (CMEs) and Their Role in Forbush Decreases

Large-scale plasma and magnetic field expulsions from the Sun's corona into space are known as CMEs. Large volumes of energy and charged particles can be released into the interplanetary medium during these eruptions, which are frequently linked to solar flares and sunspots (Aschwanden, 2006). Forbush decreases seen during solar cycle 24 at the Moscow neutron monitor have been linked to coronal mass ejections. Table lists the data for Forbush declines and related CMEs. The data analysis reveals that a total of 56 Forbush decreases (FDs) were recorded during Solar Cycle 24. Of these 56 FDs, 45 (80.36%) were linked to coronal mass ejections (CMEs), while 11 (19.64%) were not. The associations rates of Halo-type and Partial-Halo type CMEs are 64.44% & 34.78%, respectively, and the majority of related CMEs are Halo CMEs.

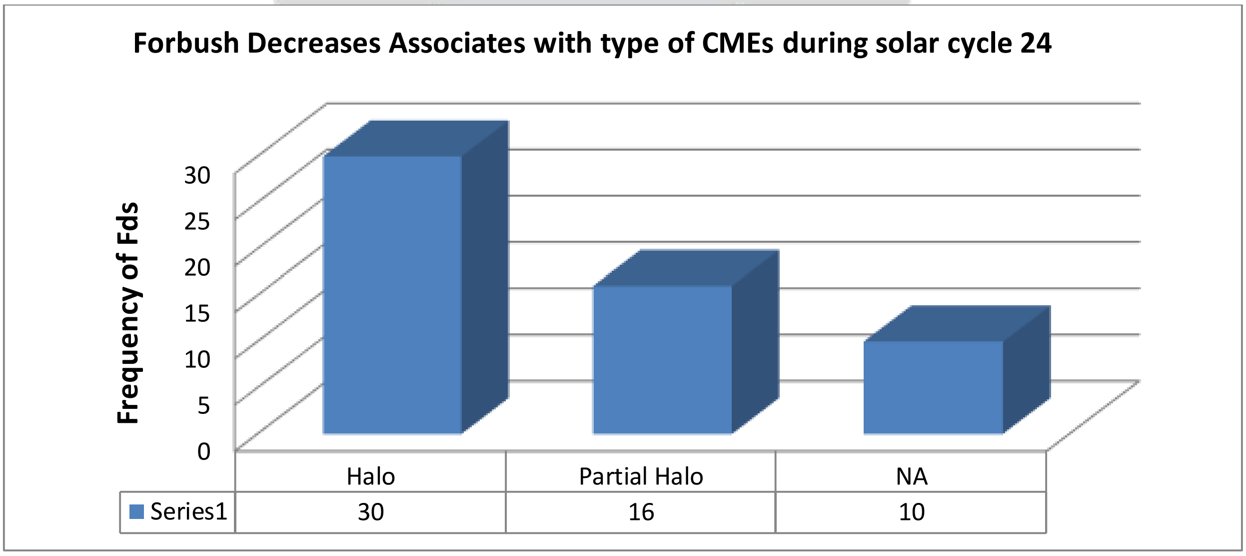

Figure-1 The bar diagram of Fds and types of related CMEs for the period of solar cycle 24.

To investigate the relationship between the size of Forbush decreases and the speed of connected CMEs, a scatter plot of the magnitude of Fds vs the speed of connected CMEs has been constructed. The scatter plot that results is shown. Refer to Figure (2). The trend line in the figure shows that the speed of related CMEs and the size of Forbush drops (FDs) are positively correlated. The correlation coefficient formula indicates a positive relationship between the speeds of related CMEs and the magnitudes of Fds, with a correlation coefficient of 0.28. This shows that CMEs are responsible for Forbush decreases.

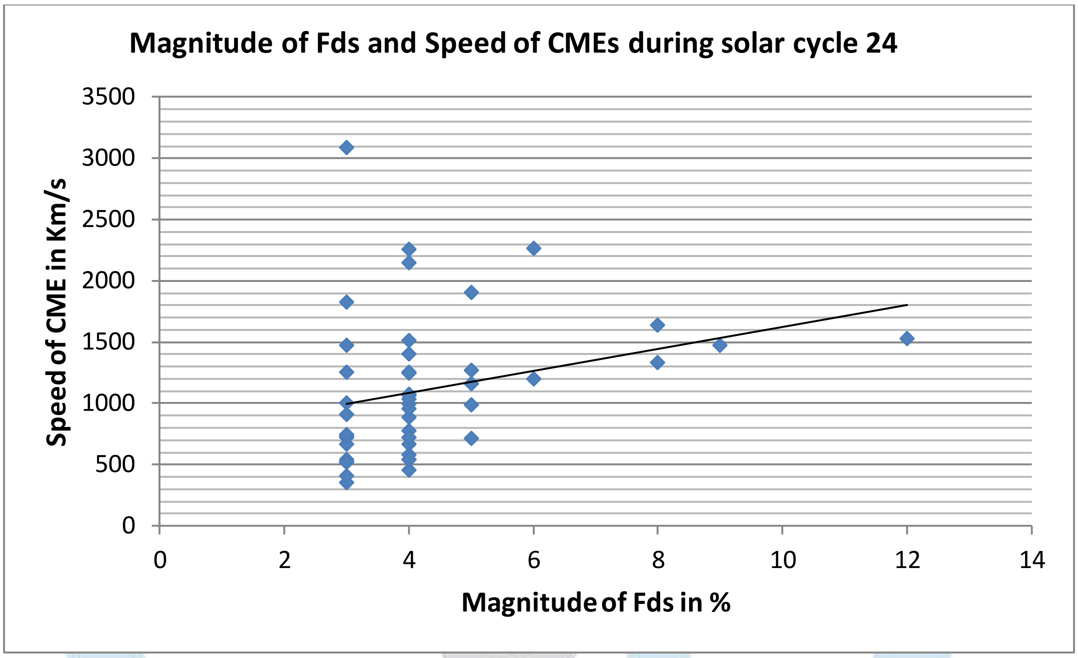

Figure-2 The scatter plot of the speed of related CMEs and the magnitude of Fds for SC 24 demonstrates a positive co-relation with a co-relation co-efficient of 0.28.

3.2 IMF Configuration and Cosmic Ray Modulation: IMF Related Forbush Decreases (FDs)

CME is a giant blast of plasma and magnetic field from the Sun's corona (exterior atmosphere). These eruptions cause interplanetary shock and Fds because of interplanetary magnetic fields (IMFs), which launch trillions of tons of stuff into space at high speeds. CMEs causes significant changes in the strength and direction of IMF, changes in IMF caused by CMEs scatter cosmic rays, leading to a decrease in the number of cosmic rays called Forbush decreases. The IMFs collides with and affects the Earth's magnetosphere, reducing the cosmic rays reaching the Earth (Groth et al., 2000). Massive amounts of magnetized plasma, also known as ICMEs or ejecta, are launched into interplanetary space by CMEs. They contribute significantly to the solar wind and have the ability to raise geomagnetic activity when they impact with the Earth's magnetosphere. A shock is produced when the ejecta's average speed exceeds that of the upstream SW. FD is a decline in the CR intensity brought on by significant IMF changes brought on by interplanetary shocks (Chauhan et al., 2019).

This section links Forbush decreases (FDs) associated with CMEs that were recorded at the Moscow neutron monitor during solar cycle 24 to interplanetary magnetic field disturbances. The analysis reveals that every one of the 56 Forbush decreases (FDs)—100% of them—is linked to interplanetary disturbance (IMF). For the analysis of CME-associated FDs and the highest value of related disturbance in IMF events, a scatter diagram showing the correlation between the magnitude of FDs and the highest value of related disturbance in IMF events has been generated. The resultant plot is seen in Figure (3). It is clear from the figure (3) that a majority of the more significant Forbush decreases (FDs) are linked to IMF disturbance occurrences with a greater highest value. However, there is no constant ratio between these two occurrences. Additionally, some FDs with higher magnitude values are associated with IMF disturbance events that have a relatively low highest value, and some FDs with low magnitude values are related with IMF disturbance events that have a relatively large highest value. The scatter plot's trend line suggests that there is a positive relationship between the peak value of IMF disturbance events and the size of Forbush declines (Fds). Between these two events, the statistical correlation coefficient is 0.24.

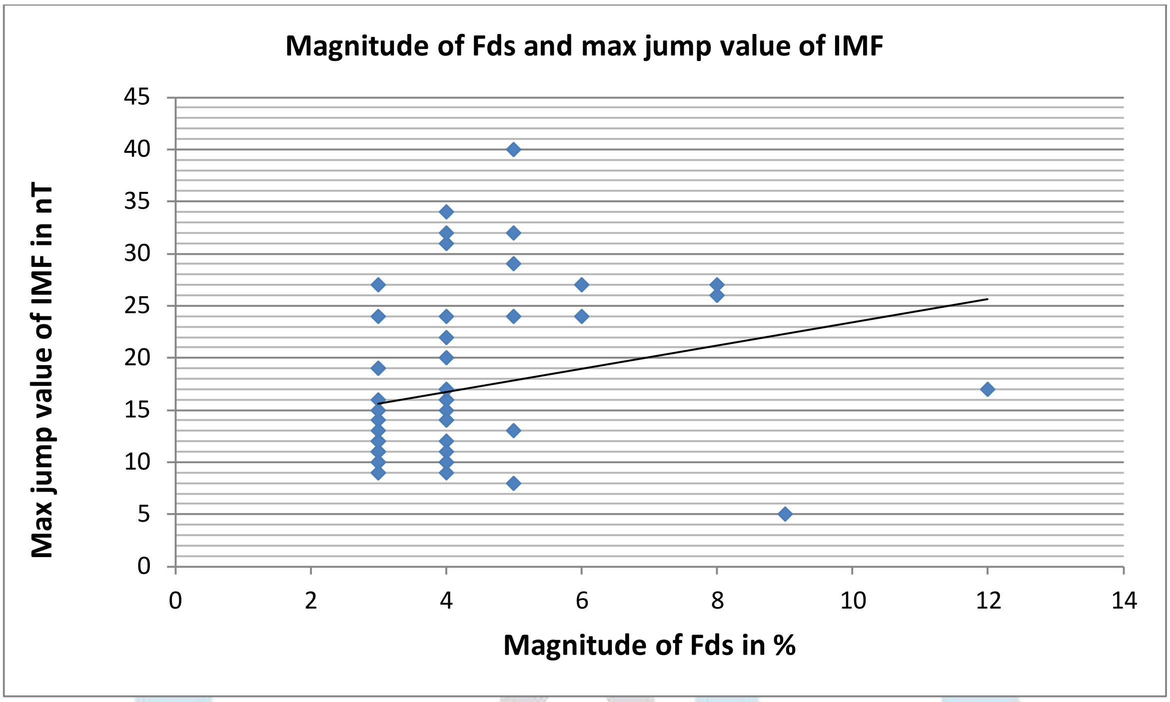

Figure-3 The scatter plot between magnitude of Forbush Decreases (Fds) and max jump value of Interplanetary Magnetic field (IMF) for the period of solar cycle 24 showing positive correlation with correlation coefficient 0.24.

To determine how Fds statistically behave in relation to the magnitude of IMF event disturbances. Figure (4) plots a scatter diagram between the magnitude of linked disturbances in IMF and the magnitude of Fds. It is clear from the figure (4) that the majority of Forbush reductions (Fds) of larger magnitudes are linked to these higher magnitude IMF disturbance episodes. However, there is no set ratio between these two occurrences. Apart from this, some Forbush decreases whose magnitude is high are associated with IMF disturbances whose magnitude is low. Whereas some Forbush decreases whose magnitude is low are associated with IMF disturbances whose magnitude is high. A positive association between the magnitude of Fds and the disturbances in IMF events may be deduced from the scatter plot's trend line. Between these two occurrences, the statistically determined correlation coefficient is 0.25.

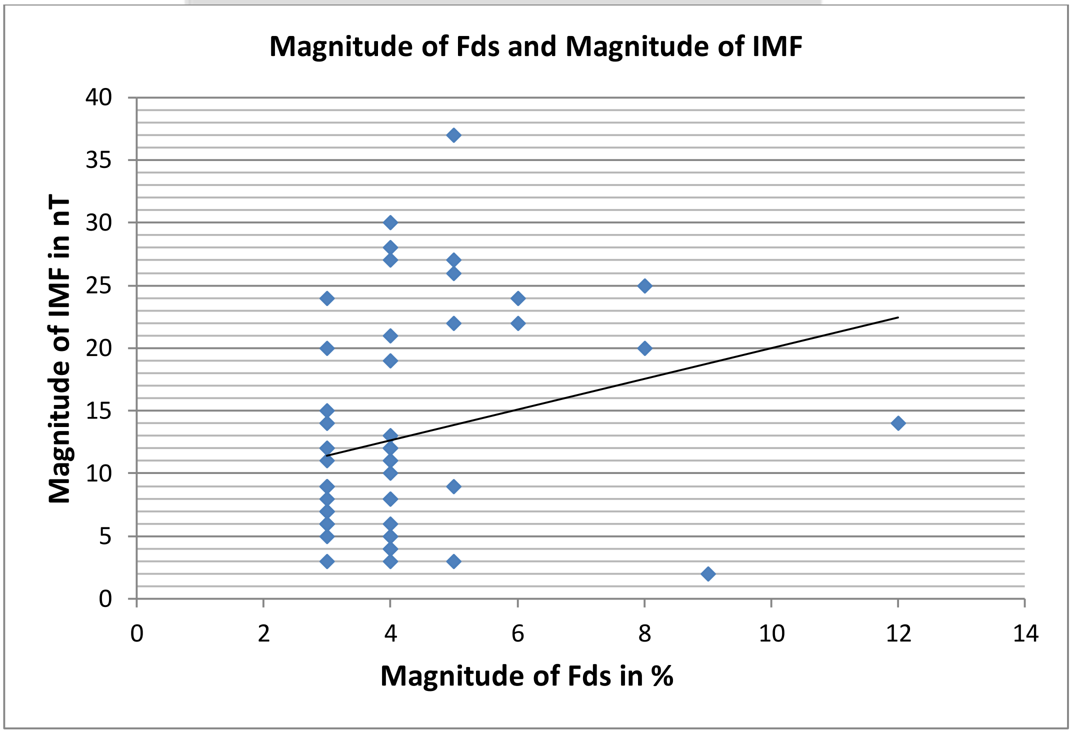

Figure-4 The scatter plot of the interplanetary magnetic field (IMF) magnitude and the Forbush Decreases (Fds) magnitude for solar cycle 24 demonstrates a positive link with a correlation coefficient of 0.25.

3.3 -Association of Forbush decreases (Fds) with X- Ray Solar Flares for the period of Solar Cycle 24.

At the solar surface, magnetic energy abruptly reconnects, resulting in solar flares. This event releases enormous amounts of energy, which is emitted as radiation in the electromagnetic radiation (such as X-rays, ultraviolet rays) and energetic particles (such as protons and electrons). During solar cycle 24, we examined FDs linked to various kinds of X-ray solar flares. Listed Table presents the data for these Forbush decreases (FDs) and their corresponding X-ray solar flares. Our data analysis revealed 56 Forbush decreases, 94.64% of these outbursts were linked to various types of X-ray solar flares. Out of the 56 FDs, 9 (16.07%) have been connected to solar flares of the X-Class, 18 (32.14%) to M-Class solar flares, 17 (20.35%) to C-Class solar flares, and 9 (16.07%) to B-Class solar flares. Figure (5) displays a bar chart that illustrates the relationship between the types of X-ray solar flares and the frequency of connected Forbush decreases (Fds). Based on these findings, it is determined that X-ray SFs are strongly connected with Forbush decreases (Fds).

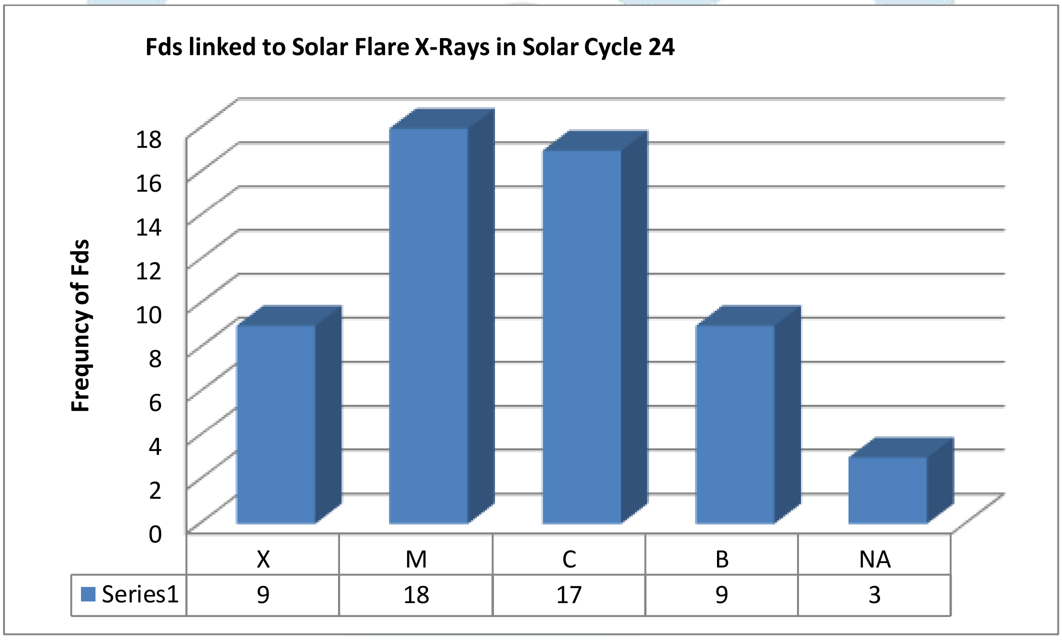

Figure-5 Indicates a bar graph over the duration of solar cycle 24 that compares the frequency of related Forbush decreases (Fds) with the various types of X-ray solar flares (SFs).

4-Main Results

1) A large percentage of Fds are linked to halo and Partial Halo CMEs. With a correlation coefficient of 0.28, it has been found that the magnitude of Forbush drops (Fds) and the speed of related CMEs are positively correlated.
2) Maximum (94.64%) Fds are linked to several categories of X-ray solar flares (SFs).
3) The magnitude of Forbush decreases (Fds) and the peak value of the corresponding interplanetary magnetic field (IMF) have been found to be positively correlated, with a correlation coefficient of 0.24.
4) The magnitude of the linked interplanetary magnetic field (IMF) and the magnitude of Forbush decreases (Fds) have been found to positively correlate, with a correlation coefficient of 0.25.

5-Conclusion

The complex interplay between solar activity, the IMF and CR modulation is highlighted by the Forbush decreases during solar cycle 24. Although solar cycle 24 had relatively low solar activity, some important CMEs still affected cosmic ray flux, resulting in detectable Forbush decreases. These occurrences highlighted the role of both the IMF and CMEs in affecting the cosmic ray environment and offered important information on the processes involved in cosmic ray modulation.

We have determined that the interplanetary magnetic field (IMF) and coronal mass ejections (CMEs) linked to hard X-ray solar flares (SFs) are more efficient in producing Forbush Decreases (Fds) in cosmic ray intensity.

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