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Forbush Decreases in Cosmic Ray Intensity with Solar and Interplanetary Activity Parameters During Decay Phase of Solar Cycle 24

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Abstract

We have analyzed Forbush decreases (Fds) observed at Oulu Super Neutron Monitor (NM) during the period of decline phase of solar cycle 24 with solar and interplanetary phenomena, coronal mass ejections (CMEs), solar flares (SFs), magnetic clouds (MCs) and disturbances in solar wind plasma velocity (SWPV). We have observed that majority of the Forbush decreases (Fds) are associated with halo, partial halo coronal mass ejections (CMEs) and magnetic clouds (MCs). Large positive correlation with correlation coefficient 0.82 has been found between magnitude of Forbush decreases (Fds) and speed of associated CMEs. Moreover, disruptions in solar wind plasma velocity (SWPV) and other types of X-ray solar flares (SFs) are linked to all of the Forbush declines. Large positive correlation with correlation coefficient 0.60 has been found between magnitude of Forbush decreases (Fds) and peak value of associated disturbances in SWPV and 0.58 between magnitude of Fds and magnitude of associated disturbances in SWPV. We have also observed that all the Forbush decreases (Fds) are associated with geomagnetic storms (GMs). The magnitude of Fds and the corresponding geomagnetic storms (GMs) have been found to positively correlate, with a correlation coefficient of 0.41. We have concluded that coronal mass ejections (CMEs) associated with hard X-ray solar flares (SFs) and magnetic clouds (MCs) are much more effective to generate Forbush decreases (Fds) in cosmic ray intensity.

1. Introduction

The intensity of galactic cosmic rays remains constant in time and space outside the heliosphere, within the heliosphere, due to various dynamic processes occurring in the sun, which extend into interplanetary space, there are long-term and short-term fluctuations in the intensity of cosmic rays. Forbush decreases fall into the category of short-term decreases, characterized by a rapid decline followed by a gradual near-exponential recovery over a few days. These decreases have been extensively studied to locate their solar source (Duggal et al. 1977) in the interplanetary structure (Bavassano et al. 1994, Cane, H. V. 1993, 2000, Lockwood et al. 1991, Zhang G. et al. 1988) and the mechanism(s) that play an important role in this phenomenon (Barouch et al. 1975, Cane et al. 1996, Richardson, 2004). Several researchers have studied Forbush decreases in cosmic ray intensity with solar activity parameters, 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) studied cosmic ray intensity variations with coronal mass ejections and concluded that CMEs are large-scale phenomena that change the configuration of the interplanetary magnetic field (IMF) and clearly modulate the cosmic ray intensity for a short (small) time days) timeline. Short-term drops in cosmic ray intensity linked to solar flares, related interplanetary magnetic fields, and radio bursts were investigated by Badruddin and Y P Singh (2003). Most of the flares associated with increases in IMF intensity and/or solar wind speed are associated with large-amplitude short-period cosmic ray decrease, which are also associated with type IV ray events. Badruddin (2003) studied the short-term cosmic ray determination by interplanetary shocks and reported that a sharp decrease in intensity begins at the arrival of certain shocks and continues until the postshock turbulent envelope passes. He further suggested that turbulent shocks are much more effective than non-turbulent shocks in generating asymmetric cosmic ray intensity suppressors (Fds). Manoharan et al. (2004) analyzed the variation of cosmic ray intensity with solar–planetary parameters and found a strong relationship between interplanetary CME–solar activity parameters and interplanetary shock and cosmic ray intensity variations. Ifedili (2006) studied two-phase Forbes descents (Fds) with coronal mass ejections, magnetic clouds, interplanetary shocks and interplanetary disturbances, interplanetary magnetic field (magnitude and direction). A mantle of slow solar wind-driven interplanetary coronal mass ejection (ICME) is upstream of the ICME due to a fast forward shock and large fluctuations of the IMF in that mantle, which has maintained the Forbush depletion (FD) of cosmic ray intensity. He has concluded that two-step Forbush decreases are due to the structure within the interplanetary shocks and sheath preceding the interplanetary coronal mass ejections. The modulation structures of quasi-symmetric short-lived Forbush depressions were examined by Chuchkov et al. (2009). The conclusion is that these Forbush counts were recorded due to stations flying through coronal mass ejection regions. Gopalswamy N (2009) and Richardson I G and Cane H V (2011) studied recurrent Forbush landings (FDs) with coronal mass ejections and their interplanetary counterparts and concluded that recurrent Forbush landings are caused by interactions between coronal mass ejections (CMEs) and their planets are equivalent to ICMEs. In their 2010 study, Papaioannou et al. examined how cosmic ray strength decreased with solar-planetary parameters and came to the conclusion that magnetic clouds, the fast solar wind stream, and interplanetary shock waves could all be to blame for the short-term variations in CR intensity. Rechardson and Cane (2011) investigated the fall of Forbush with magnetospheric and interplanetary coronal mass ejections and found that magnetospheric clouds are more likely to be involved in the deepest subsidence of the GCR than non-magnetic cloud ICMEs during 1995–2009. Chertok et al. (2013) examined the connections between the parameters of these solar flares and the features of Forbush decreases (FD) brought on by CMEs from the solar disk's central zone during solar cycle 23, On the other hand, to CME-related EUV dimming and the concentrated negligible magnetic flux of arcades. This discharge parameter has a clear direct correlation with the FD magnitude and a prominent inverse correlation with the Sun-to-Earth ICME transit time. They concluded that the main quantitative properties of the main non-repetitive FDs are largely determined by the parameters of solar radiation, especially, for example, the combined magnetic flux of dimming and arcing. Seongsuk Lee et al (2015) studied simultaneous and non-simultaneous FD events and concluded that the variation of cosmic ray intensity during the main phase is larger for simultaneous FD events than for non-simultaneous events. Hubert G. et al (2019) studied Forbes decreases with various solar and interplanetary parameters and concluded that these decreases are strongly related to coronal mass ejections (CMEs) and their interplanetary manifestations. Petukhova and others (2019) studied the weakening of the Forbush decreases are due to the influence of magnetic clouds, and they concluded that cosmic ray losses in the regions connecting the magnetic cloud and the Sun account for the magnitude of the second phase of the Forbush drops. Athanasios Papaioannou et al (2020) have studied FDs that were associated with a sudden storm commencement (SSC) at Earth, and ICME’s they have concluded that that both the shock sheath and deep GCR depressions require the ejecta, and faster-propagating ICMEs require a larger FD amplitude.

2. Data Reduction and Analysis

		Fds		GMs		CMEs		MC			SWPV	
S.No.	Date	Onset set time dd (hh)	Fd s	Onset set time dd (hh)	GM	Type H/P	Speed K/s	Class	Magnetic Cloud		Peak value of SWPV in Km/s	Magnitu de of SWPV in km/s
1	09/02/2015	09(04)	7	08(05)	-44	P	315	M-15	Na	Na	556	124
2	16/03/2015	16(20)	5	16(03)	-234	H	719	M-18	16(14)	3	614	287
3	04/05/2015	04(18)	4	Na	Na	H	753	B-97	06(12)	1	468	111
4	20/06/2015	20(18)	10	22(13)	-198	H	1305	M-15	23(02)	2	673	337
5	10/07/2015	10(02)	4	11(00)	-35	P	427	M-27	Na	Na	622	260
6	06/11/2015	06(18)	4	06(19)	-87	H	578	M-19	06(06)	1	670	202
7	03/02/2016	03(20)	5	02(20)	-57	P	540	C-18	05(19)	2	468	91
8	23/03/2016	23(04)	4	24(21)	-24	Na	Na	C-27	Na	Na	530	133
9	14/05/2016	14(20)	5	12(07)	-42	Na	Na	C-18	Na	Na	464	143
10	19/07/2016	19(18)	4	20(03)	-26	H	340	B-40	19(07)	1	563	235
11	14/10/2016	14(20)	4	13(06)	-110	P	277	B-11	12(06)	1	521	160
12	20/11/2016	20(04)	4	Na	Na	P	225	B-19	Na	Na	609	268
13	27/5/2017	27(04)	4	26(22)	-125	Na	Na	B-38	27(22)	1	401	102
14	17/07/2017	17(18)	8	16(09)	-72	H	1200	M-20	16(15)	1	625	312
15	06/09/2017	06(18)	10	06(21)	-122	H	1418	M-10	06(20)	2	750	318
16	16/02/2018	16(12)	4	15(22)	-28	H	661	C-12	Na	Na	525	177

In this work Forbush decreases (Fds) in cosmic ray intensity has been studied with different solar features, interplanetary and geomagnetic parameters. For this study the data of hourly count rates of Oulu super neutron monitors over the period of decline phase of solar cycle 24 has been used. The data of different types of coronal mass ejections are taken from SOHO – large angle spectrometric, coronagraph (SOHO / LASCO) and extreme ultraviolet imaging telescope (SOHO/EIT) sdata. The data of magnetic cloud/ejecta, interplanetary shocks are taken from shocks arrival derived by WIND group from WIND observations, ACE list of transient and disturbances. To determine disturbances in geomagnetic fields and solar wind plasma parameters, hourly data of Dst index and solar wind plasma velocity, has been used, these data has also been taken from omni web data (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. Utilized are solar STP data (http://www.ngdc.noaa.gov/stp/solar/solardataservices.html.), the NOAA monthly issue, and the Department of Commerce. In this investigation Forbush decreases (Fds) has been analyzed with coronal mass ejections and other geomagnetic and solar features associated interplanetary parameters such as, solar flares, geomagnetic storms, solar wind parameters with magnetic clouds plasma velocity of the solar wind during solar cycle 24's decrease phase and find the correlation between them.

3. Data Analysis and Results

3.1 Association of Forbush decreases (Fds) with Coronal Mass Ejections (CMEs) During Decline Phase of Solar Cycle 24

We have associated Forbush decreases observed during the decline phase of solar cycle 24 at Oulu super neutron monitor with coronal mass ejections. The data of Forbush decreases and associated CMEs are listed in Table. From the data analysis we have found total numbers of Forbush decreases (Fds) observed during the decline phase of solar cycle 24 are16. Out of 16 Forbush decreases (Fds). There is evidence linking 13 Fds (81%) to coronal mass ejections (CMEs). The association rates of H Type and P Type CMEs have been determined to be 61.54% and 38.56%, respectively, with halo CMEs calculating the majority of related CMEs.

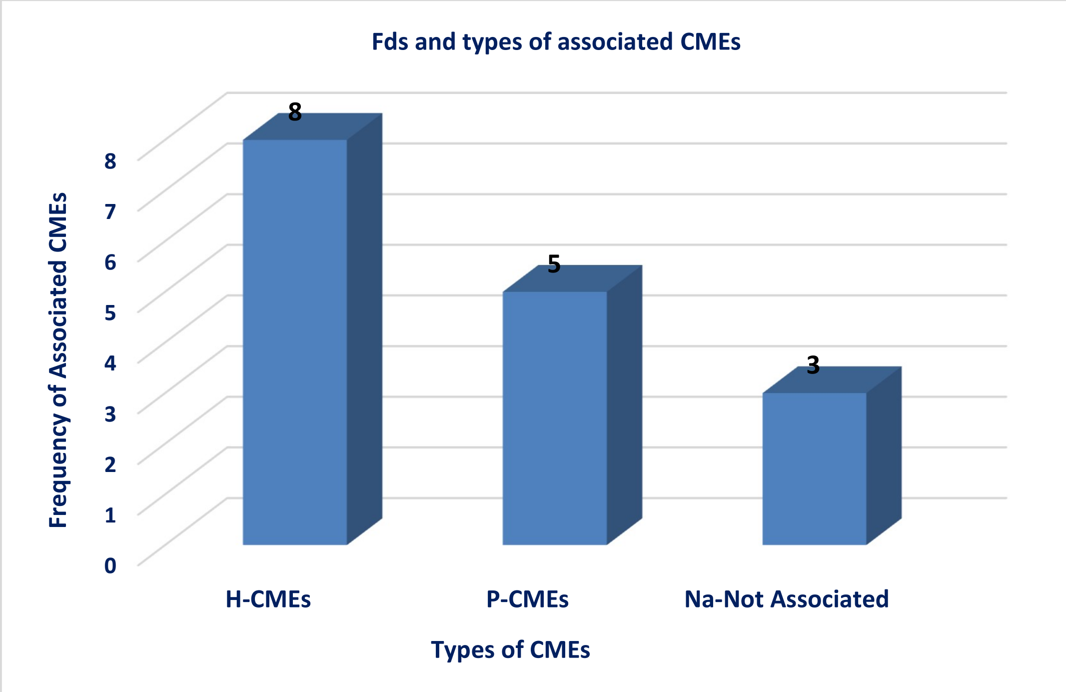

Fig.1 Shows bar diagram of Forbush decreases and types of associated CMEs for the period of decline phase of SC 24.

A scatter plot has been created between the magnitude of Forbush decreases (Fds) and the speed of associated CMEs in order to demonstrate how the two variables are related. The resulting scatter plot is displayed under Figure 2. The trend line of the figure shows large positive correlation between magnitude of Forbush decreases (Fds) and speed of associated CMEs. The correlation coefficient formula has revealed a positive association between the speed of connected CMEs and the magnitudes of Forbush decreases (Fds), with a correlation coefficient of 0.82.

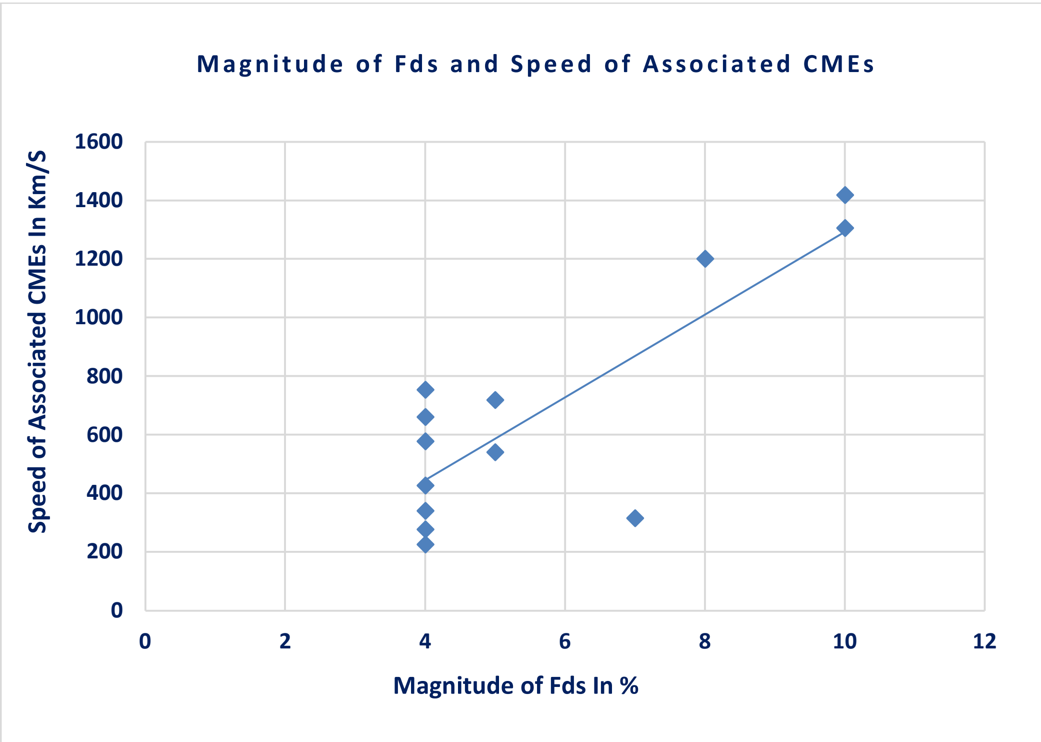

Fig.2 displays a scatter plot of the speed of related CMEs and the amount of Forbush decreases (Fds) during the decline phase of solar cycle 24, indicating a strong positive association with a correlation coefficient of 0.82.

3.2 Association of Forbush decreases (Fds) with X- Ray Solar Flares Solar During Decline Phase of Solar Cycle 24.

We have analyzed Forbush decreases (Fds) with X ray solar flares of different categories, observed during the period of decline phase of solar cycle 24. The data of such Forbush decreases (Fds) and associated X-ray solar flares are given in table. From the data examination, we have obtained 16 Forbush decreases and all the Fds (100%) are found to be related with X-ray solar flares of different categories. Out of 16 Fds, 7(43.75%) are found to be linked with M-Class solar flares. 4(25%) are linked with C-Class solar flares 5 (31.25%) are found to be linked with B- Class solar flares. Figure 3 displays a bar graph comparing the frequency of related Forbush decreases (Fds) with the types of X-ray solar flares. From these results it is concluded that Forbush decreases (Fds) are closely related with X-ray solar flares.

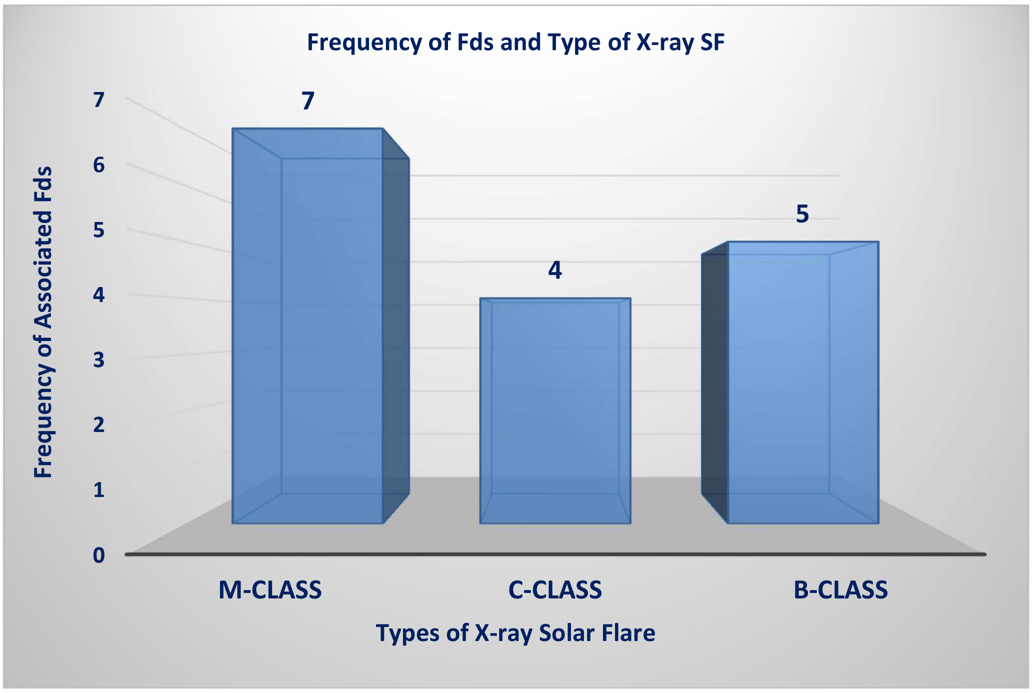

Fig.3 displays a bar graph for the Decline phase of Solar Cycle 24 that compares the frequency of related Forbush decreases (Fds) with the various forms of X-ray SF.

3.3 Statistical Relation between Forbush decrease and Magnetic Clouds During Decline Phase of Solar Cycle 24

A magnetic cloud is a region that has a smoothly changing (rotating) magnetic field, low proton temperature, low proton β, and a strong magnetic field (Burlaga et al. 1981). Magnetic clouds are frequently preceded by upstream sheaths, where the magnetic field is highly turbulent and the plasma is typically hot and dense (Tsurutani and Gonzalez, 1997). The "boundary" of the sheath could be a pressure pulse, a shock, a structure that resembles a shock, or an abrupt rise in temperature, velocity, or density. All observed MCs exhibit an increase in density, but about one-fourth do not have an upstream pressure pulse or shock (Wu and Lepping 2002). Here we attempt to associate Forbush decreases observed during the period of decline phase of solar cycle 24 with magnetic clouds. The table contains information about Forbush reductions and related magnetic clouds. From the data analysis of Forbush decreases and magnetic clouds, we have detected 10 out of 16 Fds are related with magnetic clouds of different qualities. For further analysis, we have plotted a bar diagram of the frequency of Forbush decreases and associated magnetic clouds of different qualities in figure 4. From the figure it is observed that 06 (60%,) out of 16Forbush decreases are related with excellent quality, 3 (30%) out of 16 Forbush decreases are found to be linked with good quality and 1 (10%) out of 82 are accompanying with poor quality magnetic clouds.

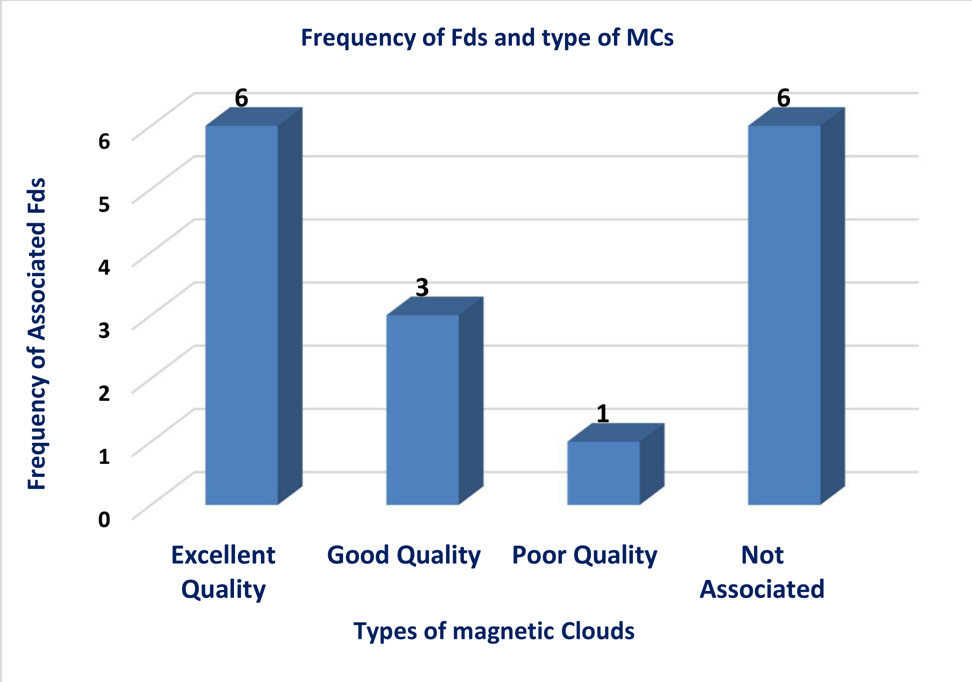

Fig.4 Shows association of Forbush decreases magnitude with quality of magnetic clouds during decline phase of SC 24.

3.4 Association of Forbush decreases (Fds) with Geomagnetic Storms During Decline Phase of Solar Cycle 24

Forbush decreases observed during the period of decline phase of solar cycle 24 at Oulu super neutron monitor has been studied with geomagnetic storms. For this study we have listed Forbush decreases and associated geomagnetic storms in table. From the data analysis given in table, we have found 16 total number of Forbush decreases during the period of decline phase of solar cycle 24. Out of these 16 Forbush decreases 14 (87.5%) Forbush decreases have been found to be associated with geomagnetic storms. Additionally, we have created a scatter map that shows the relationship between the size of related geomagnetic storms and the magnitude of Forbush decreases. The scatter plots obtained between these two parameters are shown in Figure 5. The trend line of the figure shows positive correlation between magnitude of Forbush decreases and magnitude of geomagnetic storms. Positive co-relation with co-relation with correlation coefficient 0.41 has been found between magnitudes of Forbush decreases and magnitude associated geomagnetic storms.

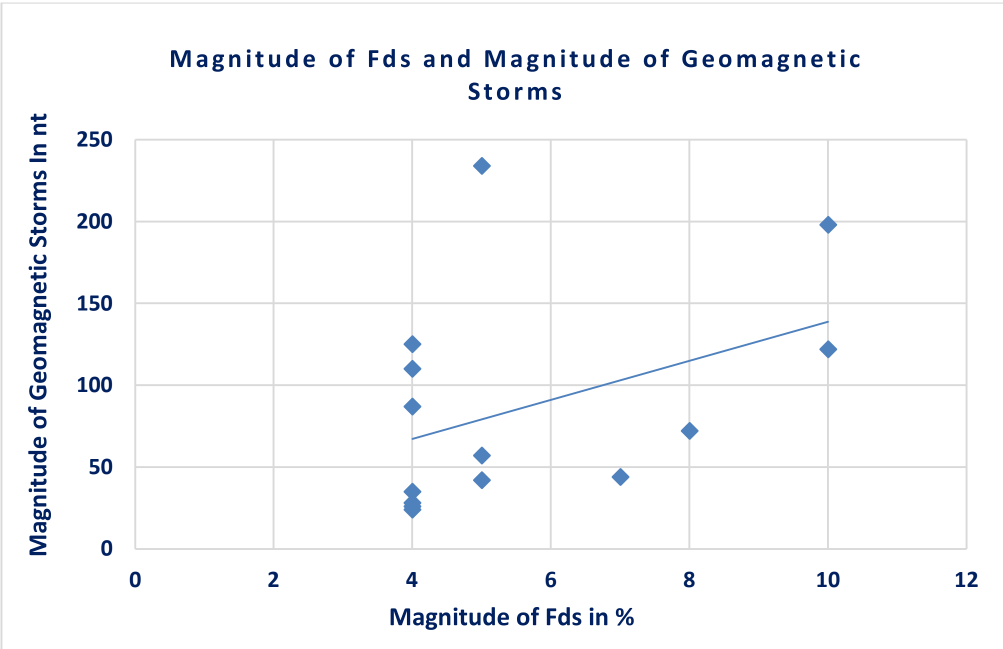

Fig.5 displays a scatter plot for the decline phase of solar cycle 24 between the magnitude of associated geomagnetic storms and the magnitude of Fds.

3.5 Association of Forbush decreases (Fds) with Disturbances in Solar Wind Plasma Velocity During Decline Phase of Solar Cycle 24

In this section we associated Forbush decreases (Fds) observed at Oulu super neutron monitor during the period of decline phase of solar cycle 24 with disturbances in solar wind plasma velocity (SWPV). The data of observed Forbush decreases (Fds) and associated disturbances in solar wind plasma velocity (SWPV) is given in table, it is observed that we have 16 Forbush decreases (Fds) out which all Fds (100%) Forbush decreases (Fds) have been found to be associated with disturbances in solar wind plasma velocity (SWPV) events. To know the statistical behavior of Forbush decreases (Fds) with disturbances in solar wind plasma velocity (SWPV) events we have plotted a scatter diagram between magnitude of Forbush decreases (Fds) and peak value of associated SWPV events and the resulting plot is shown in **Figure 6.** From the figure of scatter plot it is seen that most of the Forbush decreases (Fds) of higher magnitudes are associated with such SWPV events having higher peak value but we have some point in scatter plot which shows some Forbush decreases (Fds) of higher magnitude are associated with such disturbances in solar wind plasma velocity which low peak value of velocity and some point which implies some Forbush decreases (Fds) of small magnitude are associated with such SWPV events which have high peak value of velocity. Thus, there is no set proportionality between these two occurrences. From the trend line of the scatter plot, it may be inferred that there is large positive correlation between magnitude of Forbush decreases (Fds) and peak value of SWPV events. Statistically calculated co-relation co-efficient is 0.60 between these two events.

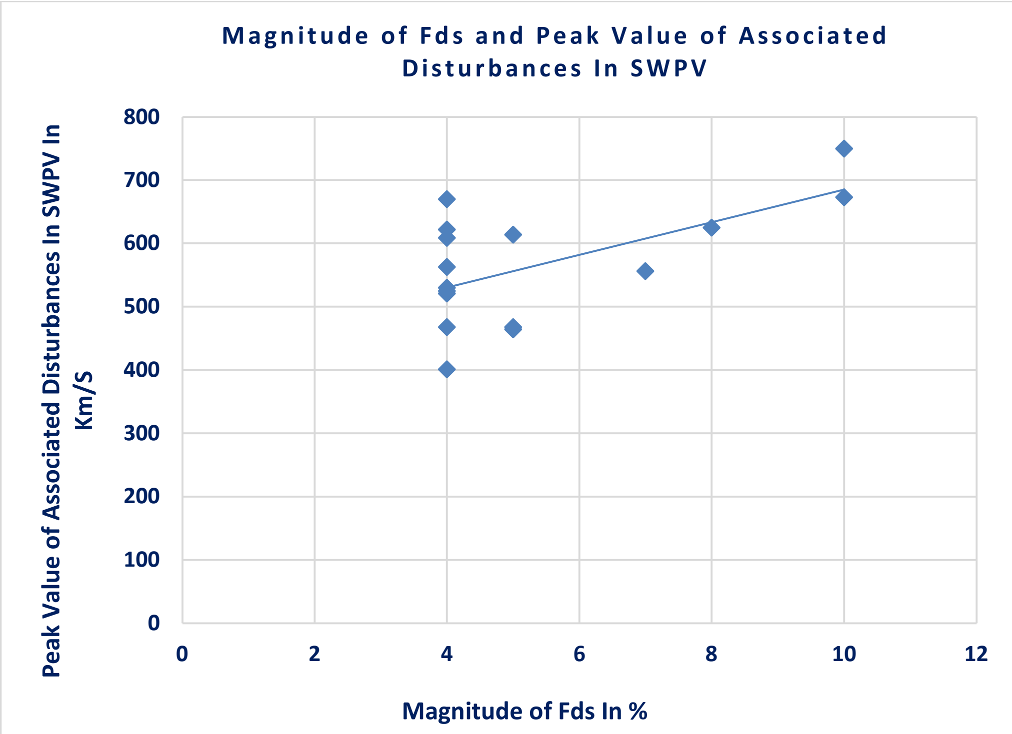

Fig.6 Shows scatter plot between magnitude of Forbush decreases (Fds) and peak value of associated disturbances in (SWPV) events. Showing positive correlation with correlation coefficient 0.60.

To know the statistical behavior of Forbush decreases (Fds) with magnitude of SWPV) events we have plotted a scatter diagram between magnitude Forbush decreases (Fds) and magnitude of associated disturbances in SWPV and the resulting plot is shown in Figure 7. From the figure it is inferred that, most of the Forbush decreases (Fds) of higher magnitudes are associated with such SWPV events having higher magnitude but these two events do not have any fixed proportion, we have found some Forbush decreases (Fds) which have higher magnitude value but they are associated with such SWPV events which have relatively small magnitude and vice versa. From the trend line of the scatter plot, it may be inferred that there is positive correlation between magnitude of Forbush decreases (Fds) and magnitude of SWPV events. Statistically calculated co-relation co-efficient is 0.58 between these two events.

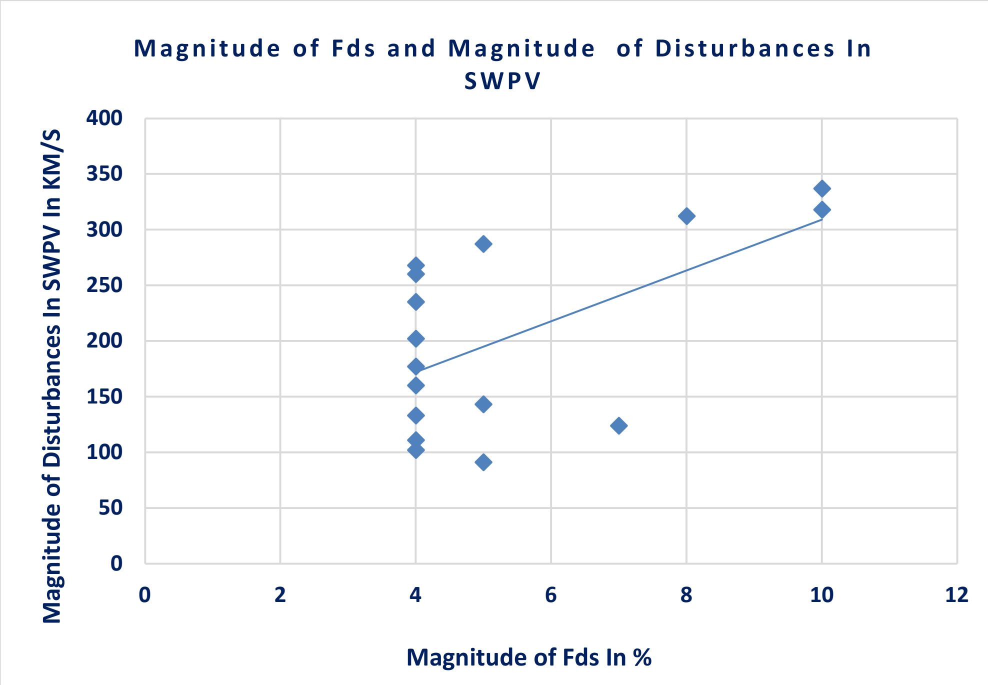

Fig.7 Shows scatter plot between magnitude of Forbush decreases (Fds) and magnitude of associated disturbances in (SWPV) events. Showing positive co-relation with correlation coefficient 0.58.

4. Main Results

1) Majority of the Forbush decreases (Fds) are associated with halo, partial halo coronal mass ejections (CMEs). Large positive correlation with correlation coefficient 0.82 has been found between magnitude of Forbush decreases (Fds) and speed of associated CMEs.
2) Majority of the Forbush decreases 62.5% are linked with and magnetic clouds, we have detected 10 out of 16 Fds are related with magnetic clouds of different qualities and magnetic clouds (MCs).
3) All the Forbush decreases are associated with X-ray solar flares (SFs) of different categories
4) All the Forbush decreases are associated with disturbances in solar wind plasma velocity (SWPV). Large positive correlation with correlation coefficient 0.60 has been found between magnitude of Forbush decreases (Fds) and peak value of associated disturbances in SWPV.
5) Positive correlation with correlation coefficient 0.58 has been found between magnitude of Forbush decreases (Fds) and magnitude of associated disturbances in SWPV.
6) All the Forbush decreases (Fds) are associated with geomagnetic storms (GMs). The magnitude of Fds and the corresponding geomagnetic storms (GMs) have been found to positively correlate, with a correlation coefficient of 0.41.

5. Conclusion

We have concluded that coronal mass ejections (CMEs) associated with hard X-ray solar flares (SFs) and magnetic clouds (MCs) are much more effective to generate Forbush decreases (Fds) in cosmic ray intensity. The Forbush decreases are also related to disturbances solar wind plasma velocity and geomagnetic storms in geomagnetic fields.

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Conflict of Interest

The authors of this manuscript declare that they have no conflicts of interest.

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