Solar and interplanetary causes of x-class, x-ray solar flare related Forbush decreases of higher magnitude in cosmic ray intensity during the period of solar cycle 23 and rising phase of solar cycle 24

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Abstract
Forbush decreases (Fds) of higher magnitude associated with X-Class X-ray solar flares observed during the period of solar cycle 23 and rising phase of 24 (1997-2012) have been studied with solar and interplanetary parameters. It is observed that all the Forbush decreases (Fds) are associated with halo and partial halo coronal mass ejections (CMEs), and most of them (82.35%) are higher speed CMEs with speed >1000Km/s. A large positive correlation with a correlation coefficient of 0.68 has been found between the magnitude of Forbush decreases (Fds) and the speed of associated CMEs. Further, all these Forbush decreases (Fds) have been identified as being associated with fast forward interplanetary shocks and disturbances in solar wind plasma parameters. Positive correlations with correlation coefficient 0.44 and 0.37 have been determined between magnitudes of Forbush decreases (Fds), and peak value and magnitude of associated disturbances in solar wind plasma temperature, 0.32 and 0.42 between the magnitude of Forbush decreases (Fds) and peak value and magnitude of associated disturbances in solar wind plasma density. Positive correlations with correlation coefficient 0.32 have also been determined between magnitudes of Forbush decreases (Fds) and the peak value of associated disturbances in solar wind plasma velocity.

Keywords: X-ray solar flares, Forbush decreases (Fds), Coronal Mass Ejections (CMEs), Interplanetary Shocks, Solar Wind Disturbances.

1. Introduction
Forbush decreases are transient depressions in the galactic cosmic ray intensity which are characterized by a sudden onset, reaching a minimum within about a day, followed by a more gradual recovery phase typically lasting several days. These decreases are strongly related to coronal mass ejections (CMEs) and their interplanetary manifestation’s (Cane et al. 1996, 2000, Badruddin 1997, 2000, 2002, 2003, Y.P Singh et al 2005, Cane and Richardson, 2003, Badruddin, 1997, Kota 2001, Morfill, 1979, Richardson, et al 1996, Richardson, et al 1999, Richardson, 2004, Cliver et al 2003, Cane at al 1996, Hubert G. et all 2019). Cane et al (1997) have reported that the depth of Forbush events depends upon the trajectory of interplanetary coronal mass ejection. Ifedili S.O (2004) has studied two-step asymmetric cosmic ray intensity decreases (Fds) with coronal mass ejections (CMEs) magnetic clouds, interplanetary shocks and interplanetary disturbances, interplanetary magnetic field and concluded that interplanetary coronal mass ejection (ICME) impacting on the slow solar wind, there is a sheath upstream of the ICME led by a fast forward shock and the large IMF variations in this sheath, which sustained the Forbush decreases (Fds) in the cosmic ray intensity. Badruddin (2003) has reported that abrupt onset of the decrease in intensity starts upon the arrival of certain shocks and decreases continue till the passage of post-shock turbulent sheath. He has further reported that turbulent shocks are much more effective in producing asymmetric cosmic ray intensity decreases (Fds) than non-turbulent shocks. Zhang and Burlaga (1988) concluded that relatively large decreases in cosmic ray intensity are associated with magnetic clouds that are preceded by a shock, whereas only a small decrease in cosmic ray intensity is associated with magnetic clouds that are not preceded by shock. Petukhova et al (2019) have studied Forbush decreases with magnetic clouds they concluded that the cosmic ray losses at the regions connecting the magnetic cloud with
the Sun determine the amplitude of the second step of Forbush decrease. The time dependence of the Forbush decrease characteristics on magnetic cloud type is determined. The referred results show a prominent role of the magnetic field structure in the time dynamics of the Forbush decrease. Seongsuk Lee et al (2015) have 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 ones.

2. Experimental Data

In this study, Forbush's decrease of higher magnitude and associated with X-Class X-Ray solar flares observed from 1997 to 2012 have been studied with coronal mass ejections and interplanetary parameters interplanetary shocks, and disturbances in solar wind plasma parameters. In this study, Forbush decreases ≥ 5% has been taken into consideration. The data of Forbush decreases, hourly count rate of the Oulu super neutron monitor (NM) has been used. For the determination of disturbances in solar wind plasma parameters, solar wind plasma temperature velocity, density hourly of data of these parameters has been used and taken from Omni web data (http://omniweb.gsfc.nasa.gov/form/dxi.html)). The data of coronal mass ejections (CMEs) have been taken from SOHO – large-angle spectrometric, coronagraph (SOHO / LASCO), and extreme ultraviolet imaging telescope (SOHO/EIT) data. The data of X-ray solar flares are taken from STP solar data(http://www.ngdc.noaa.gov/stp/solar/solardataseservices.html). The data of interplanetary shocks are taken from the list of the shocks observed by PM and WIND satellites.

Table -1: Forbush decreases of higher magnitude associated with X-Class X-ray solar flares and associated Coronal Mass Ejections and Interplanetary shocks.

| S.N O | Date       | Onset set time dd hh | Max. dec. time dd hh | Recovery time dd hh | Mag % | Arrival Time dd(hh) | Date time dd(hh) | Type H/P | Speed K/s | Date time dd(hh) | Class |
|-------|------------|-----------------------|----------------------|---------------------|-------|---------------------|-----------------|----------|-----------|-----------------|-------|
| 1     | 25.08.98   | 25(12)                | 26(08)               | 28(16)              | 8     | 26(07)              | nd              | nd       | nd        | 24(22)          | X10   |
| 2     | 08.06.00   | 08(08)                | 09(00)               | 17(00)              | 8     | 08(09)              | 06(16)          | H        | 1130      | 06(16)          | X-23  |
| 3     | 15.07.00   | 15(12)                | 16(04)               | 18(16)              | 12    | 15(15)              | 14(11)          | H        | 1674      | 14(11)          | X-57  |
| 4     | 26.11.00   | 26(12)                | 27(08)               | 02(08)              | 8     | 26(08)              | 24(05)          | H        | 1298      | 24(05)          | X-20  |
| 5     | 27.08.01   | 27(18)                | 28(08)               | 03(20)              | 7     | 27(20)              | 25(17)          | H        | 1433      | 25(16)          | X-53  |
| 6     | 21.10.01   | 21(16)                | 22(04)               | 25(04)              | 5     | 21(17)              | 19(170)         | H        | 901       | 19(16)          | X-16  |
| 7     | 06.11.01   | 06(00)                | 06(16)               | 08(20)              | 12    | 06(02)              | 04(17)          | H        | 1810      | 04(16)          | X-10  |
| 8     | 15.12.01   | 15(00)                | 17(12)               | 19(16)              | 5     | na                  | 13(15)          | H        | 864       | 13(14)          | X-62  |
| 9     | 30.12.01   | 30(16)                | 03(04)               | 08(20)              | 5.5   | 30(20)              | 28(20)          | H        | 2239      | 28(20)          | X-34  |
| 10    | 29.05.03   | 29(16)                | 31(04)               | 04(20)              | 7     | 29(12)              | 27(24)          | H        | 964       | 27(23)          | X-13  |
| 11    | 29.10.03   | 29(00)                | 29(16)               | 04(20)              | 25    | 29(06)              | 28(11)          | H        | 2686      | 28(10)          | X-172 |
| 12    | 07.01.04   | 07(00)                | 09(00)               | 13(16)              | 8     | 06(20)              | 06(06)          | P        | 1469      | 06(06)          | X     |
| 13    | 21.01.04   | 21(16)                | 22(12)               | 27(12)              | 8     | 22(01)              | 20(00)          | H        | 1074      | 20(07)          | X     |
| 14    | 07.11.04   | 07(08)                | 10(00)               | 18(00)              | 12    | 07(03)              | 07(17)          | H        | 1759      | 07(16)          | X-20  |
| 15    | 11.09.05   | 11(00)                | 11(12)               | 21(05)              | 12    | 11(01)              | 09(20)          | H        | 2257      | 09(19)          | X-62  |
| 16    | 14.12.06   | 14(18)                | 15(000)              | 19(18)              | 10    | 14(14)              | 13(02)          | H        | 1931      | 13(02)          | X-34  |
| 17    | 25.09.11   | 25(12)                | 26(18)               | 5(12)               | 6     | 26(12)              | 22(10)          | H        | 1905      | 22(10)          | X-14  |
| 18    | 14.07.12   | 14(18)                | 15(12)               | 18(18)              | 7     | 14(17)              | 12(16)          | H        | 1092      | 12(16)          | X-14  |
Table-2 Forbush decreases of higher magnitude and associated disturbances in solar wind plasma parameters.

| Date         | Forbush decreases(Fds) | Jump in Solar Wind Temperature (JSWT) | Jump in Solar Wind Density(JSWD) | Jump in solar wind Velocity(JSWV) |
|--------------|------------------------|--------------------------------------|---------------------------------|----------------------------------|
|              | Date                   | Onset set time dd (hh) | mag% | Start time dd(hh) | Peak Temperature In Deg. K | Magnitude of Jump in Deg k | Start time dd(hh) | Peak Density Value n/cc | Magnitude of Jump n/cc | Start time dd(hh) | Peak Velocity Km/s | Magnitude of Jump km/s |
| 25.08.98     | 25(12)                 | 8                      | 26(01) | 1042930 | 967337 | 25(19) | 9.5 | 6.4 | 25(23) | 858 | 466 |
| 08.06.00     | 08(08)                 | 8                      | 08(03) | 887701 | 781686 | 08(08) | 19.2 | 15.8 | 08(08) | 773 | 253 |
| 15.07.00     | 15(12)                 | 12                     | 14(07) | 676914 | 583648 | 14(14) | 26.6 | 24.3 | 14(12) | 882 | 209 |
| 26.11.00     | 26(12)                 | 8                      | 26(08) | 594388 | 552597 | 26(11) | 35.4 | 29.3 | 26(03) | 624 | 252 |
| 27.08.01     | 27(18)                 | 7                      | 27(07) | 348295 | 160985 | 27(09) | 13.1 | 6.1 | 27(07) | 558 | 34 |
| 21.10.01     | 21(16)                 | 5                      | 21(15) | 502256 | 422395 | 21(13) | 22.2 | 16.4 | 21(10) | 677 | 360 |
| 06.11.01     | 06(00)                 | 12                     | 5(10)  | 136839 | 105551 | 05(09) | 46.1 | 31.4 | 05(14) | 426 | 141 |
| 15.12.01     | 15(00)                 | 5                      | 14(18) | 137313 | 105398 | 15(19) | 31.8 | 21.4 | 14(19) | 350 | 69 |
| 30.12.01     | 30(16)                 | 5.5                    | 30(02) | 61712  | na     | na     | na     | na     | na     | na     |
| 29.05.03     | 29(16)                 | 7                      | 29(14) | 497719 | 489103 | 29(14) | 50.3 | 24.2 | 29(14) | 799 | 103 |
| 29.10.03     | 29(00)                 | 25                     | 28(08) | na     | 979536 | 28(01) | na     | na     | na     | na     | na |
| 07.01.04     | 07(00)                 | 8                      | 06(18) | 636415 | 555367 | 06(15) | 5.6  | 3.1  | 06(18) | 723 | 155 |
| 21.01.04     | 21(16)                 | 8                      | 21(12) | 553467 | 509255 | 21(23) | 18.3 | 13.1 | 21(16) | 666 | 163 |
| 07.11.04     | 07(08)                 | 12                     | 07(10) | 1793947 | 786124 | 07(03) | 75.1 | 54.1 | 07(09) | 726 | 386 |
| 11.09.05     | 11(00)                 | 12                     | 11(00) | 2083103 | 1876759 | 10(22) | 25   | 22.5 | 10(20) | 1059 | 346 |
| 14.12.06     | 14(18)                 | 10                     | 13(12) | 265379 | 240834 | 13(03) | 10   | 9.3  | 13(06) | 512 | 312 |
| 25.09.11     | 25(12)                 | 6                      | 25(18) | 1007504 | 983838 | 25(06) | 30.7 | 27   | 25(05) | 689 | 381 |
| 14.07.12     | 14(18)                 | 7                      | 14(08) | 556783 | 544250 | 14(05) | 20.2 | 16.2 | 14(08) | 667 | 357 |

3. Data Analysis and Results

The data of Forbush decreases, associated coronal mass ejections, and X-ray solar flares are listed in Table 1. From the data analysis, it is observed that all the X-Class, X-ray solar flare-related Forbush decreases (Fds) is associated with halo and partial halo coronal mass ejections (CMEs). We have 18 Forbush decreases in our list and have no data of CME for one Forbush decrease event for the association. Out of 17 Forbush decreases all are associated with coronal mass ejections (CMEs). The association rates of halo and partial halo coronal mass ejections have been found 94.11% and 5.88% respectively. It is also determined that the majority (82.35%) of the associated CMEs are of higher speed CMEs with speed >1000Km/s. A large positive correlation with a correlation coefficient of 0.68 has been found between the magnitude of Forbush decreases (Fds) and the speed of associated CMEs.

![Figure-1 Shows scatter plot between the magnitude of Forbush decreases and speed of associated CMEs showing positive correlation with correlation coefficient 0.68.](image-url)
From the further analysis of Forbush decreases of selected criteria, and associated interplanetary shocks it is observed that most of the Forbush decreases (94.44%) are associated with interplanetary shocks and associated shocks are forward shocks. The occurrences of most of the Forbush decreases (88.24%) are found in the ± time lag between onset time of Forbush decreases and arrival time of Interplanetary shocks.

From the data analysis of Forbush decreases and associated disturbances in solar wind plasma temperature listed in Table 2, it is observed that 88.88% of Forbush decreases are associated with a jump in solar wind plasma temperature (JSWT). To know the statistical behavior of Forbush decreases with the peak value of associated JSWT events, a scatter plot has been plotted between the magnitude of Forbush decreases and the peak value of the temperature of associated JSWT events, and the resulting plot is shown in Figure 2. From the figure, it is inferred that most of Forbush decrease of higher magnitude are associated with such JSWT events which have relatively higher peak temperature but these two events do not have any fixed proportion. We have found some Forbush decreases which have higher magnitude but they are associated with such JSWT events which have lower values of peak temperature and vice versa. A positive correlation has been found between the magnitude of Forbush decreases and the peak temperature of associated JSWT events. Statistically calculated co-relation co-efficient has been found 0.44 between these two events.

![Figure 2](image-url)  
**Figure-2** Shows scatter plot between magnitude of Forbush decreases and peak value of associated JSWT events showing positive correlation with correlation coefficient 0.44.

To know the statistical behavior of Forbush decreases with the magnitude of the jump of associated JSWT events a scatter plot has been plotted between the magnitude of Forbush decreases and magnitude of jump in solar wind plasma temperature of associated JSWT events and the resulting plot is shown in Figure 3. From the figure, it is inferred that most of Forbush decrease having higher magnitude are associated with such JSWT which have relatively higher jump magnitude of the temperature of associated JSWT events but these two events do not have any fixed proportion. We have found some Forbush decreases which have higher magnitude but they are associated with such JSWT events which have lower values of the magnitude of temperature and vice versa. A positive correlation has been found between the magnitude of Forbush decreases and the magnitude of the jump of associated JSWT events. Statistically calculated co-relation co-efficient is 0.37 between these two events.
Figure-3 Shows scatter plot between the magnitude of Forbush decreases and magnitude of the jump of associated JSWT events showing positive correlation with correlation coefficient 0.37.

From the data analysis of Forbush decreases and associated disturbances in solar wind plasma density listed in Table 2, it is observed that 88.88% of the Forbush decreases are associated with disturbances in solar wind plasma density (JSWD).

To know the statistical behavior of Forbush decreases with the peak value of associated JSWD events a scatter plot has been plotted between the magnitude of Forbush decreases and the peak value of density of associated JSWD events and the resulting plot is shown in Figure 4. From the figure, it is inferred that most of Forbush decrease having higher magnitude are associated with such JSWD events which have relatively higher peak density but these two events do not have any fixed proportion. We have found some Forbush decreases which have higher value but they are associated with such JSWD events which have lower values of peak density and vice versa. A positive correlation has been found between the magnitude of Forbush decreases and the peak density of associated JSWD events. Statistically calculated co-relation coefficient is 0.32 between these two events.

To know the statistical behavior of Forbush decreases with the magnitude of associated JSWD events a scatter plot has been plotted between the magnitude of Forbush decreases and magnitude of jump in solar wind plasma density of associated JSWD events and the resulting plot is shown in Figure 5. The trend line of the figure between the magnitude of Forbush decreases and the magnitude of jump in solar wind plasma density shows a positive correlation between these two events. A positive correlation has been found between the magnitude of Forbush decreases and the magnitude of associated JSWD events. Statistically calculated co-relation coefficient is 0.42 between these two events.

Figure-4 Shows scatter plot between the magnitude of Forbush decreases and the peak value of associated JSWD events showing positive correlation with correlation coefficient 0.32.
From the data analysis of Forbush decreases and associated disturbances in solar wind plasma velocity (JSWV) listed in Table 2, it is observed that most of the Forbush decreases are associated with disturbances in solar wind plasma velocity. We have 18 Forbush decreases in which 16 the Forbush decreases (88.88%) are associated with a jump in solar wind plasma velocity. To know the statistical behavior of Forbush decreases with the peak value of associated JSWV events a scatter plot has been plotted between the magnitude of Forbush decreases and the peak value of the velocity of associated JSWV events and the resulting plot is shown in Figure 6. From the figure, it is inferred that most of Forbush decrease having higher magnitude are associated with such JSWV events which have relatively higher peak velocity but these two events do not have any fixed proportion. We have found some Forbush decreases which have higher magnitude but they are associated with such JSWV events which have lower values of peak velocity and vice versa. A positive correlation has been found between the magnitude of Forbush decreases and peak velocity of associated JSWV events. Statistically calculated correlation co-efficient is 0.32 between these two events.

4. Main Results

All the X-Class X-Ray solar flare-related Forbush decreases are associated with coronal mass ejections. The association rates of halo and partial halo coronal mass ejections have been found 94.11% and 5.88% respectively. It is also observed that the majority (82.35%) of the associated CMEs are of higher speed CMEs with a speed >1000Km/s.

A large positive correlation with correlation coefficient 0.68 has been found between the magnitude of X-Class, X-ray solar related Forbush decreases (Fds), and speed of associated CMEs.
Most of the X-Class, X-ray solar-related Forbush decreases (94.44%) are found to be associated with interplanetary shocks and related shocks are forward shocks.

Most of the X-Class, X-ray solar-related Forbush decreases (88.88%) are associated with disturbances in solar wind plasma temperature.

A positive correlation has been found between the magnitude of Forbush decreases and the peak temperature of associated JSWT events. Statistically calculated co-relation co-efficient is 0.44 between these two events. A positive correlation has been found between the magnitude of Forbush decreases and the magnitude of associated JSWT events. Statistically calculated co-relation co-efficient is 0.37 between these two events.

Most of the X-Class, X-ray solar-related Forbush decreases (88.88%) is associated with disturbances in solar wind plasma density.

A positive correlation has been found between the magnitude of Forbush decreases and the peak density of associated JSWD events. Statistically calculated co-relation co-efficient is 0.32 between these two events.

A positive correlation has been found between the magnitude of Forbush decreases and the magnitude of associated JSWD events. Statistically calculated co-relation co-efficient is 0.42 between these two events.

Most of the X-Class, X-ray solar-related Forbush decreases are associated with disturbances in solar wind plasma velocity. We have 18 Forbush decreases in which 16 the Forbush decreases (88.88%) are associated with a jump in solar wind plasma velocity.

A positive correlation has been found between the magnitude of Forbush decreases and peak velocity of associated JSWV events. Statistically calculated co-relation co-efficient is 0.32 between these two events.

5. Conclusion

Coronal mass ejections and solar flares are drastic solar events in which a large amount of solar material is ejected from the sun into the heliosphere and produces interplanetary shocks and measure disturbances in solar wind plasma parameters. A CME ejected from the Sun moving outward in the heliosphere with a speed larger than the ambient solar wind speed and produce shock/sheath region ahead of it; the shock front hits the magnetosphere before CME which drive the shock. As the shock reaches the ground it produces a Forbush decrease in cosmic ray intensity. The results obtained from the data analysis it is concluded that Forbush decreases of higher magnitudes associated with X-Class X-Ray solar flares are caused by coronal mass ejections and interplanetary shocks that they generate. The further magnitude of Forbush decreases is closely related to the speed of CMEs and disturbances in solar wind plasma parameters.

Conflict of Interest

In this manuscript the authors declare that there is no conflict of interest.

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