

Ground level enhancement and solar wind plasma parameters during near solar maximum of solar cycle 23

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Abstract

Ground level Enhancements are sudden sharp and short-lived increase in cosmic ray intensities recorded by super neutron monitors and are known to take place during powerful solar eruptions. We have studied Ground Level Enhancement observed during the period of near solar maximum 23 with coronal mass ejections, X-ray solar flares, and disturbances in solar wind plasma parameters such as solar wind plasma pressure (SWPP) solar wind plasma velocity (SWPV) and interplanetary magnetic fields (IMF B). We have determined that all the GLE are associated with coronal mass ejection and most of them are halo coronal mass ejections, Further we have obtained that these GLEs are associated with hard X-ray solar flares and disturbances in solar wind plasma parameters We have obtained positive correlation with correlation coefficient 0.41, between maximum percentage intensity I_{max} (%) of GLEs and peak value of associated disturbances in interplanetary magnetic fields 0.31 between maximum percentage intensity I_{max} (%) of GLEs and magnitude of associated disturbances in interplanetary magnetic fields. Large positive correlation with correlation coefficient 0.61 has been determined, between maximum percentage intensity I_{max} (%) of GLEs and peak value of associated disturbances in solar wind plasma velocity and positive correlation with correlation coefficient 0.39 between maximum percentage intensity I_{max} (%) of GLEs and magnitude of associated disturbances in solar wind plasma velocity. Further Large positive correlation with correlation coefficient 0.87 has been determined, between maximum percentage intensity I_{max} (%) of GLEs and peak value of associated disturbances in solar wind plasma pressure and 0.83 between maximum percentage intensity I_{max} (%) of GLEs and magnitude of associated disturbances in solar wind plasma pressure.

Keywords: - Ground Level Enhancements (GLEs), Solar wind plasma velocity (SWPV), Solar wind plasma pressure (SWPP), Interplanetary magnetic fields (IMFB).

1. Introduction

The sporadic emission of solar relativistic charged particles causes Ground Level Enhancements (GLEs) which are increases of cosmic ray intensity measured on the earth's ground. Solar energetic particles, solar flares, and/or coronal mass ejections are also normally observed when Ground Level Enhancements occur, suggesting that these are causing Ground Level Enhancements or are caused by the same process in the sun or its corona (Mishev et al., 2013). The solar sources of the Ground Level Enhancement events are generally well-connected and hence a flare origin is often assumed. Several studies have been reported for individual locations or for a group of locations (Flückiger et al., 2005; Miyasaka et al., 2005; Moraal et al., 2005; Zhu et al., 2005). The studies of Ground Level Enhancement events are about various aspects such as, time profiles (including anisotropies at different phases of evolution), ionic charge state compositions (Labrador et al., 2005) and spectra (Mewaldt et al., 2005), probable relationships with specific flares and their evolution phases, with coronal mass ejections and interplanetary coronal mass ejections shocks and even possibility of arrival of high energy neutrons (Bieber et al., 2005a; Struminsky, 2005a, Souvatzoglou et al., 2014) and it is inferred that for Ground Level Enhancement studies, the interpretation of the magnitudes of increases needs information about the vertical cut-off rigidities, which seem to have changed with time due to secular changes in geomagnetic field (Wu et al., 2020), response functions of the neutron monitors (including angle dependent yield functions, (Clem & Dorman, 2000,), as also about the asymptotic coordinates due to deflection in geomagnetic field (Tsyganenko, 1989, Sura et al., 2020). Some other investigators have reported about the

origin of Ground Level Enhancements. Andrews [2003] suggested that the strong flares are very likely to be associated with fast coronal mass ejections. He has confirmed that most of the Ground Level Enhancements associated with strong flares are also associated with very high-speed coronal mass ejections. The association of very fast coronal mass ejections and strong solar flares during Ground Level Enhancement events indicates that the strong flare and very fast coronal mass ejections -driven shocks may cause Ground Level Enhancements. Gopalswamy, et al (2005) have studied relation between ground level enhancements and coronal mass ejections. They have inferred that GLE-associated CMEs represent the fastest known population of CMEs. In their study all the GLEs have been found to be associated with metric type II bursts. It is also suggested from the comparison between GLE and metric type II onsets that coronal shocks are formed before GLEs are released at the Sun. A few researchers (Kudela et al, 1993; Reames, 1999, B B Gvozdevsky et al 2019) insisted that GLE events are the relativistic counterparts of solar energetic particle events and caused by the sporadic emission of solar relativistic charged particles. Reames (2009) further attempted to explain the concepts of GLEs and their probable release time from the origin. He concluded that energy release of solar flare contributing to GLE occurrence and found that the initial solar particle release times occur, after the start times of radio emission. In another study, Firoz et al. ([2010b) proposed that, since solar flares are able to release relativistic high-energy particles, GLEs can be studied as the consequence of solar flares. Several researchers (Cliver, 1982; Cane et al, 2002) also agreed that the particle acceleration in solar flares might play an important role in GLE production. Ultimately, solar flares seem to be the main agent that might produce the enhancement in CRI. K. Firoz et al (2010) have studied Ground Level Enhancements with energetic solar features and for the period of 1979-2009. They have determined 32 GLEs over this period and studied characteristics of the 32-event associated solar flares, coronal mass ejections (CMEs), and solar energetic particle (SEP) fluxes. They have found that all of the 32 GLEs were associated with solar flares, CMEs, and SEP fluxes. K. A. Firoz (2010) have studied Ground level enhancement (GLE having increase rate >5%.) with solar, interplanetary and geophysical parameters for the period of 1996 –2006 and observed that the total interplanetary magnetic field (IMF-Btot) transported by the solar wind from the Sun may sometimes cause sudden increase in cosmic ray intensity because the correlations with peak ($n \leq 10$) intensities of GLEs show sometimes direct proportionality to simultaneous IMF-Btot (nT). Furthermore, the mean IMF Btot (9 nT) corresponded to peak ($n \leq 10$) intensities of GLEs is stronger than the mean IMF-Btot (6.78 nT) corresponded to the overall cosmic ray intensities. The magnetic fields were towards the Sun during the peaks of GLEs.

2. Experimental Data

Ground Level Enhancement has been studied with disturbances in solar wind plasma parameters. For the determination of Ground Level Enhancement, one minute 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 velocity, pressure, interplanetary magnetic fields 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/solardataservices.html>).

Table No 1-Ground Level Enhancements Solar Flares and Coronal Mass Ejections

S. N.	Ground Level Enhancements			Solar Flares	CMEs	CMEs Speed (km/s)
	Date	GLE Onset (Obs)	GLE int(%)			
1	14.07.2000	10:30	29.3	10:03	X5.7/N22W07	1078
2	15.04.2001	14:00	56.7	13:19	X14/S20W85	834
3	18.04.2001	2:35	13.8	2:11	?/S23W117	2465
4	04.11.2001	17:00	3.3	16:03	X1.0/N06W18	1810
5	26.12.2001	5:30	7.2	4:32	M7.1/N08W54	1785
6	24.08.2002	1:18	5.1	0:49	X3.1/S02W81	2066
7	28.10.2003	11:22	12.4	11:00	X17/S20E02	2459
8	29.10.2003	21:30	8.1	20:37	X10/S19W09	2029
9	02.11.2003	17:30	7	17:03	X8.3/S18W59	2036

Table No 2-Ground Level Enhancements and solar wind plasma parameters

Ground Level Enhancements and Associated Solar Wind plasma Parameters												
S.N	GLE Onset	GLE int(%)	Interplanetary Magnetic Field IMF			Solar Wind Plasma Velocity			Solar Wind Plasma Pressure			
			Start time in dd(hh)	Maximum IMF	Magnitude	Start time in dd(hh)	Maximum velocity in Km/s	Magnitude of V	Start time in dd(hh)	Maximum Pressure npa	Magnitude	
1	14.07.2000	10:30	29.3	15(07)	29.2	20.9	15(10)	1010	333	15(12)	30.15	22.78
2	15.04.2001	14:00	56.7	nd	nd	nd	15(19)	987	479	Nd	Nd	Nd
3	18.04.2001	2:35	13.8	18(00)	23.8	19.1	18(00)	919	559	18(00)	14.7	13.36
4	04.11.2001	17:00	3.3	05(00)	10.3	3.2	05(04)	423	57	05(06)	10.5	9.04
5	26.12.2001	5:30	7.2	27(00)	8.9	3	Nd	Nd	Nd	26(00)	10.31	8.48
6	24.08.2002	1:18	5.1	23(09)	8.6	0.9	23(06)	915	519	23(00)	7.4	5.29
7	28.10.2003	11:22	12.4	27(20)	18.4	8.8	27(21)	809	373	28(01)	6.59	5.21
8	29.10.2003	21:30	8.1	29(23)	47.3	38.1	Nd	Nd	Nd	Nd	Nd	Nd
9	02.11.2003	17:30	7	03(03)	6.4	2	03(02)	545	42	01(05)	2	0.07

3. Ground Level Enhancements in Relation with Coronal Mass Ejections and Solar Flares

The Ground level enhancements and associated coronal mass ejections are listed in table. From data analysis, it is seen that all the GLEs are associated with fast halo and partial halo CMEs. The lowest speed of CMEs is 834 Km /s and highest CMEs speed 2465 Km/s. The most of the associated CMEs are Halo CMEs. We have 09 GLEs our list out of 09, 08 CMEs are found to be associated with H type CMEs whereas 01 CME is associated with P type CME. The association rates of H and P type CMEs are 88.88 % and 11.11 % respectively. These GLEs are also associated with hard X-Ray solar flares of X-Class and M-Class solar flare association rates of X-Class and M-Class solar flares are 88.88 % and 11.11 % respectively and most of them are originating from western hemisphere of the sun.

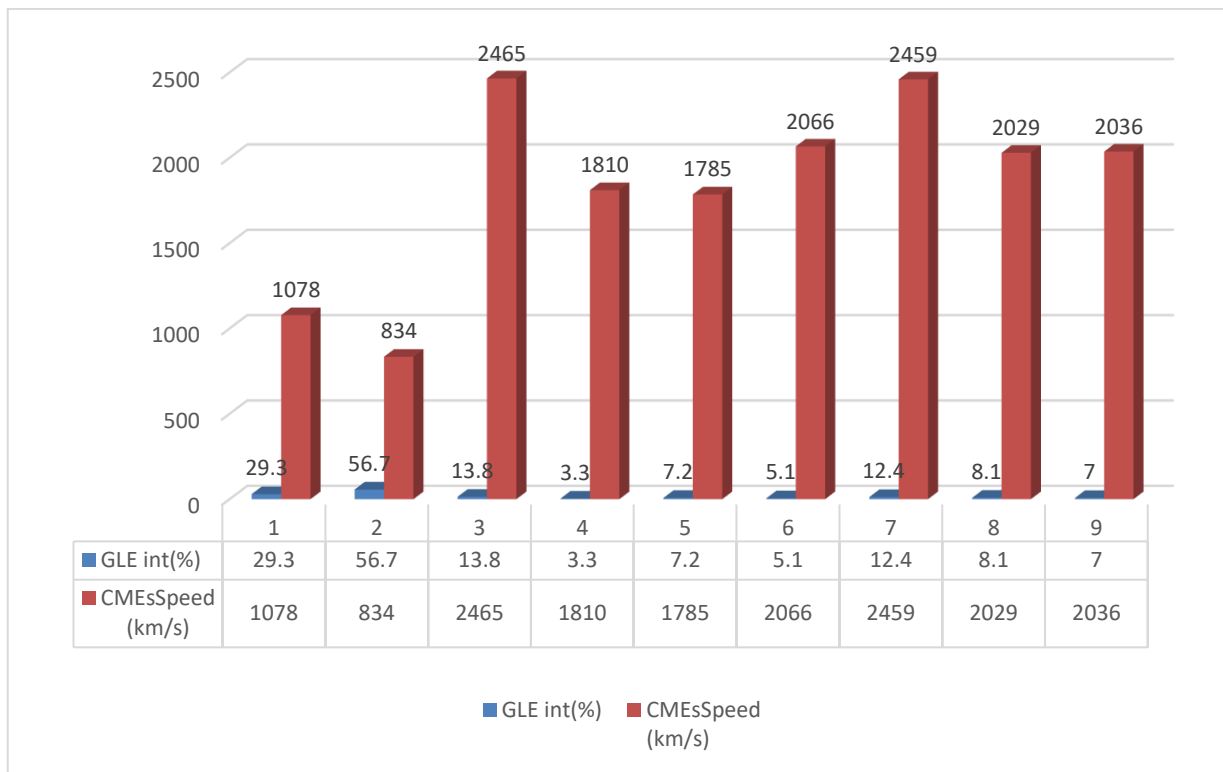


Figure-1 Shows bar graph of maximum percentage intensity of ground level enhancements and speed of associated CMEs.

4. Ground Level Enhancements in Relation with Interplanetary Magnetic Fields

4.1 Correlation with Peak Value of IMF Disturbances

We studied the Ground Level Enhancement (GLEs) observed during the period of near solar maximum of solar cycle of 23 with disturbances in interplanetary magnetic fields. The observed GLEs and associated disturbances in interplanetary magnetic fields are listed in Table. From the data analysis of the table, it is observed that we have 09 GLEs in which the

data of IMF B is not available for association of 01GLE; all08 GLEs have been found to be associated with disturbances in interplanetary magnetic fields (IMF B).

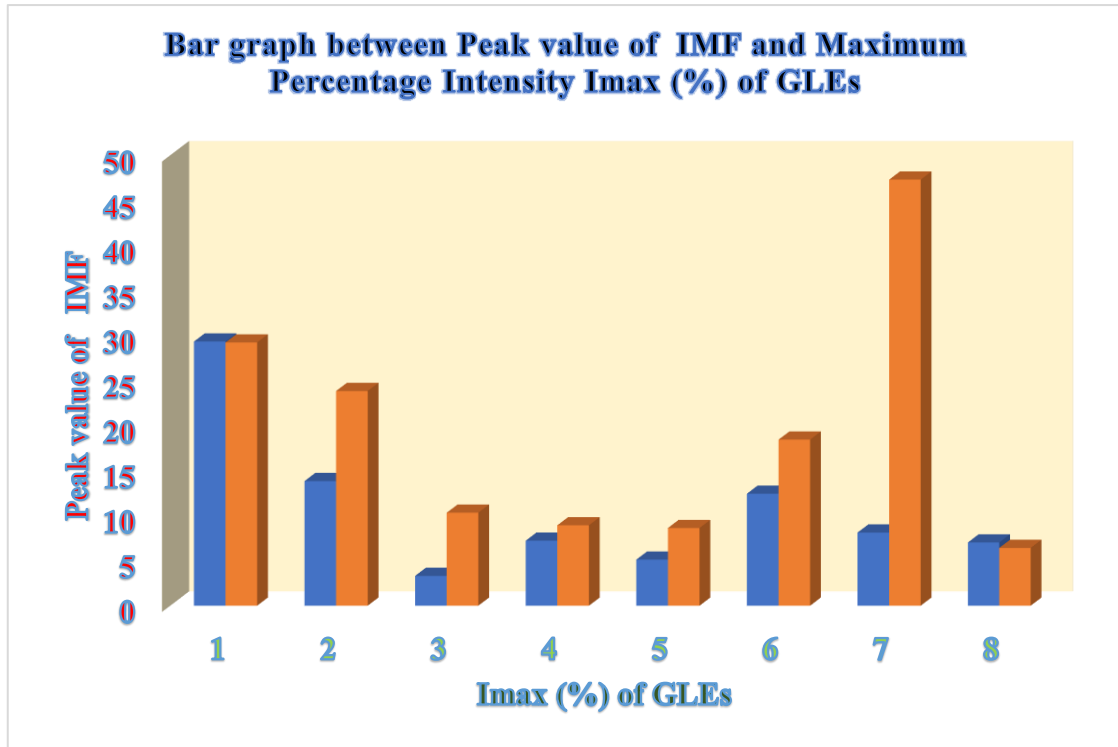


Figure-2 Shows Bar graph between Peak value of IMF and Maximum Percentage Intensity Imax (%) of GLEs

To know the statistical behavior of maximum percentage intensity of GLEs with peak value of associated disturbances in interplanetary magnetic fields (IMFB), we have plotted a bar diagram of maximum percentage intensity of GLEs and peak value of associated disturbances in IMF B in figure 2, and also a scatter plot between maximum percentage intensity of GLEs and peak value of associated disturbances in interplanetary magnetic fields in figure 3. From the figure 2 it is inferred that, most of GLEs events having higher maximum percentage intensity Imax (%) are associated with such IMF B disturbances which have relatively higher peak value but these two events do not have any fixed proportion. We have found some GLE events which have higher maximum percentage intensity but they are associated with such IMF B disturbances which have relatively lower peak values and vice versa. From the trend line of the scatter plot, it may be inferred that there is moderate positive correlation between maximum percentage intensity of GLEs and peak value of associated disturbances of IMF. Positive correlation has been found between maximum percentage intensity of GLEs and peak value of IMF B disturbances. Statistically calculated co-relation co-efficient is 0.41 between these two events.

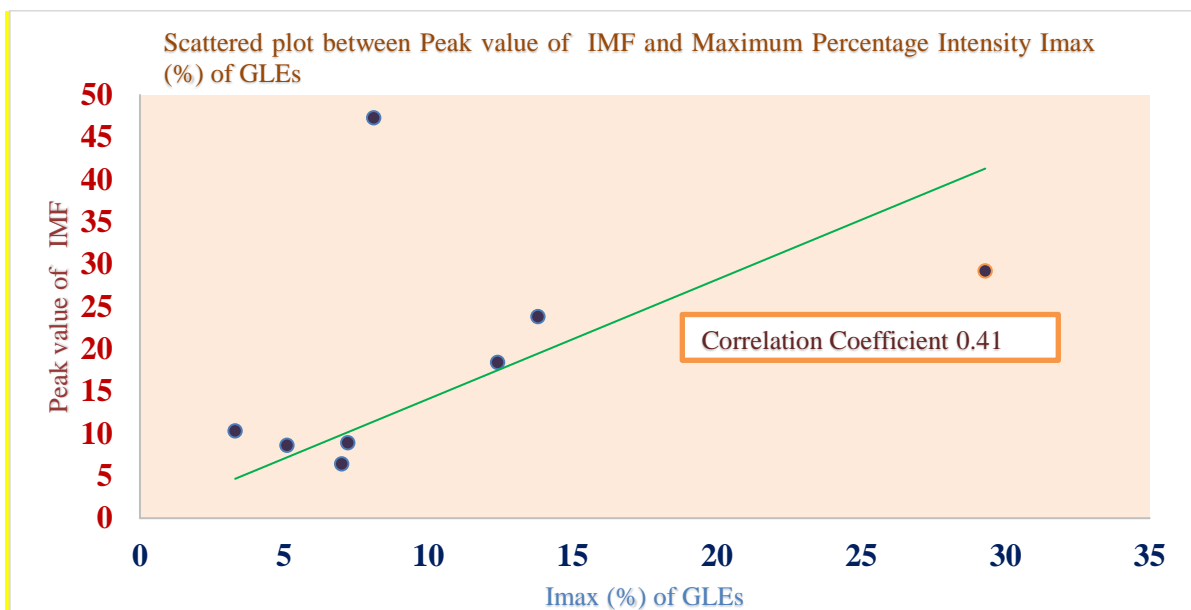


Figure-3 Scattered plot between peak value of IMF and maximum percentage intensity (Imax (%)) of GLEs.

4.2 Correlation with Magnitude of IMF Disturbances

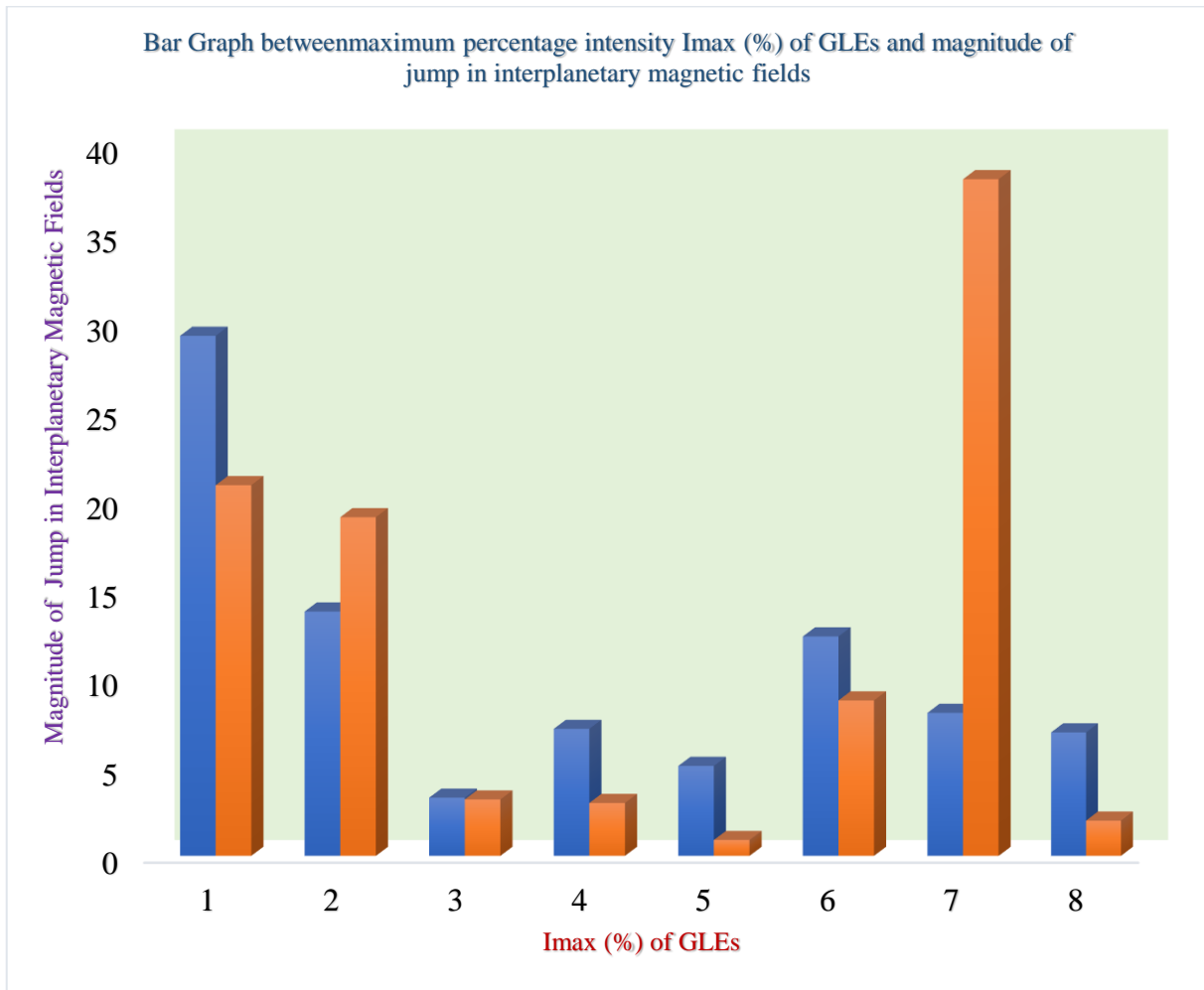


Figure-4 Shows Bar diagram of maximum percentage intensity of GLEs and Magnitude of associated disturbances in IMF.

To know the statistical behavior of maximum percentage intensity of GLEs with magnitude of associated disturbances in interplanetary magnetic fields (IMFB), we have plotted a bar diagram of maximum percentage intensity of GLEs and magnitude of associated disturbances in IMFB in figure 4, and scatter plot between maximum percentage intensity of GLEs and magnitude of associated disturbances in interplanetary magnetic fields in figure 5. From the figure 4 it is inferred that, most of GLEs events having higher maximum percentage intensity I_{max} (%) are associated with such IMF B disturbances which have relatively higher magnitude but these two events do not have any fixed proportion, We have found some GLE events which have higher maximum percentage intensity but they are associated with such IMF B disturbances which have relatively lower magnitude and vice versa. From the trend line of the scatter plot, it may be inferred that there is moderate positive correlation between maximum percentage intensity of GLEs and magnitude of associated disturbances of IMF. Positive correlation has been found between maximum percentage intensity of GLEs and magnitude of IMF B disturbances. Statistically calculated co-relation co-efficient is 0.36 between these two events.

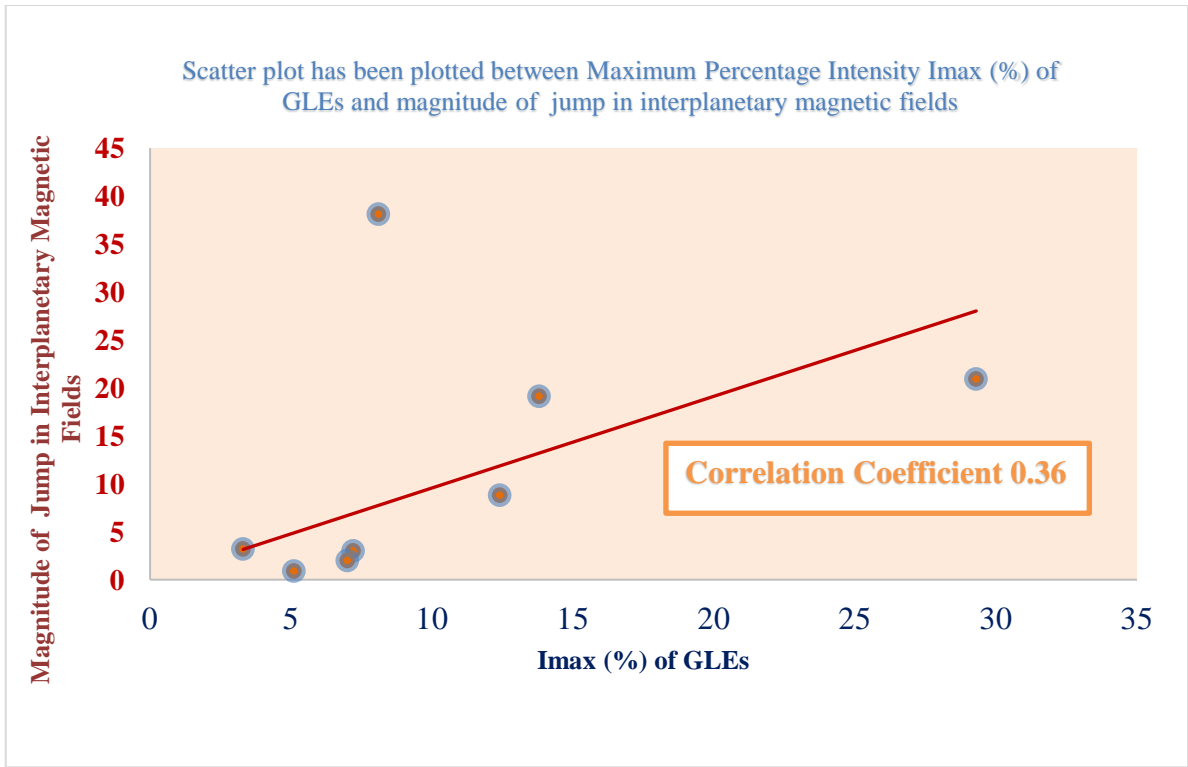


Figure-5 Scatter plot has been plotted between maximum percentage intensity I_{max} (%) of GLEs and magnitude of associated disturbances in Interplanetary Magnetic Fields (IMFB).

5. Ground Level Enhancements in Relation with Solar Wind Plasma Velocity

5.1 Correlation with Peak Value of SWPV Disturbances

We studied the Ground Level Enhancement (GLEs) observed during the period of near solar maximum of solar cycle of 23 with disturbances in solar wind plasma velocity. The observed GLEs and associated disturbances in solar wind plasma velocity are listed in Table. From the data analysis of the table, it is observed that we have 09 GLEs in which the data of SWPV is not available for association of 02 GLE, all 08 GLEs have been found to be associated with disturbances in solar wind plasma velocity.

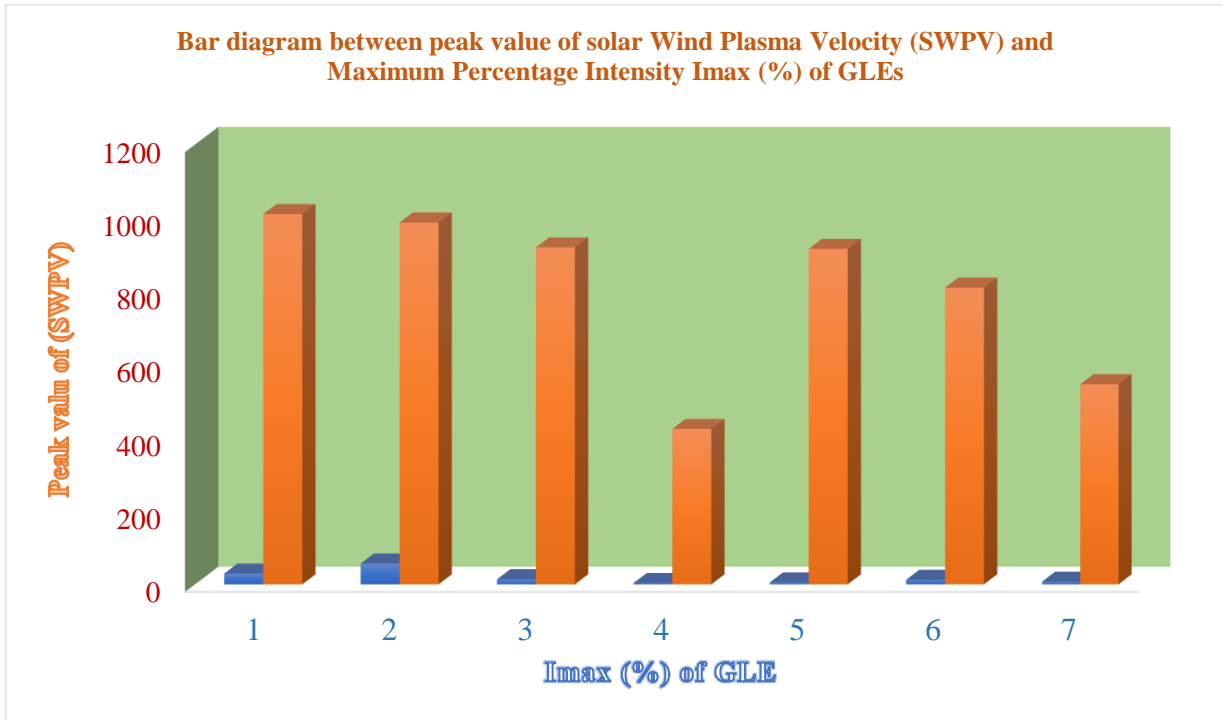


Figure-6 Bar diagram between peak value of solar Wind Plasma Velocity (SWPV) and Maximum Percentage Intensity I_{max} (%) of GLEs.

To know the statistical behavior of maximum percentage intensity of GLEs with peak value of associated disturbances in solar wind plasma velocity we have plotted a bar diagram of maximum percentage intensity of GLEs and peak value of associated disturbances in solar wind plasma velocity in figure 5, and scatter plot between maximum percentage intensity of GLEs and peak value of associated disturbances in solar wind plasma velocity in figure 6 . From the figure 5 it is inferred that, most of GLEs events having higher maximum percentage intensity I_{max} (%) are associated with such SWV disturbances which have relatively higher peak value but these two events do not have any fixed proportion, We have found some GLE events which have higher maximum percentage intensity but they are associated with such SWV disturbances which have relatively lower peak flux and vice versa .From the trend line of the scatter plot, it may be inferred that there is large positive correlation between maximum percentage intensity of GLEs and peak value of associated disturbances of SWV disturbances .Positive correlation has been found between maximum percentage intensity of GLEs and peak value of SWV disturbances. Statistically calculated co-relation co-efficient is 0.61 between these two events.

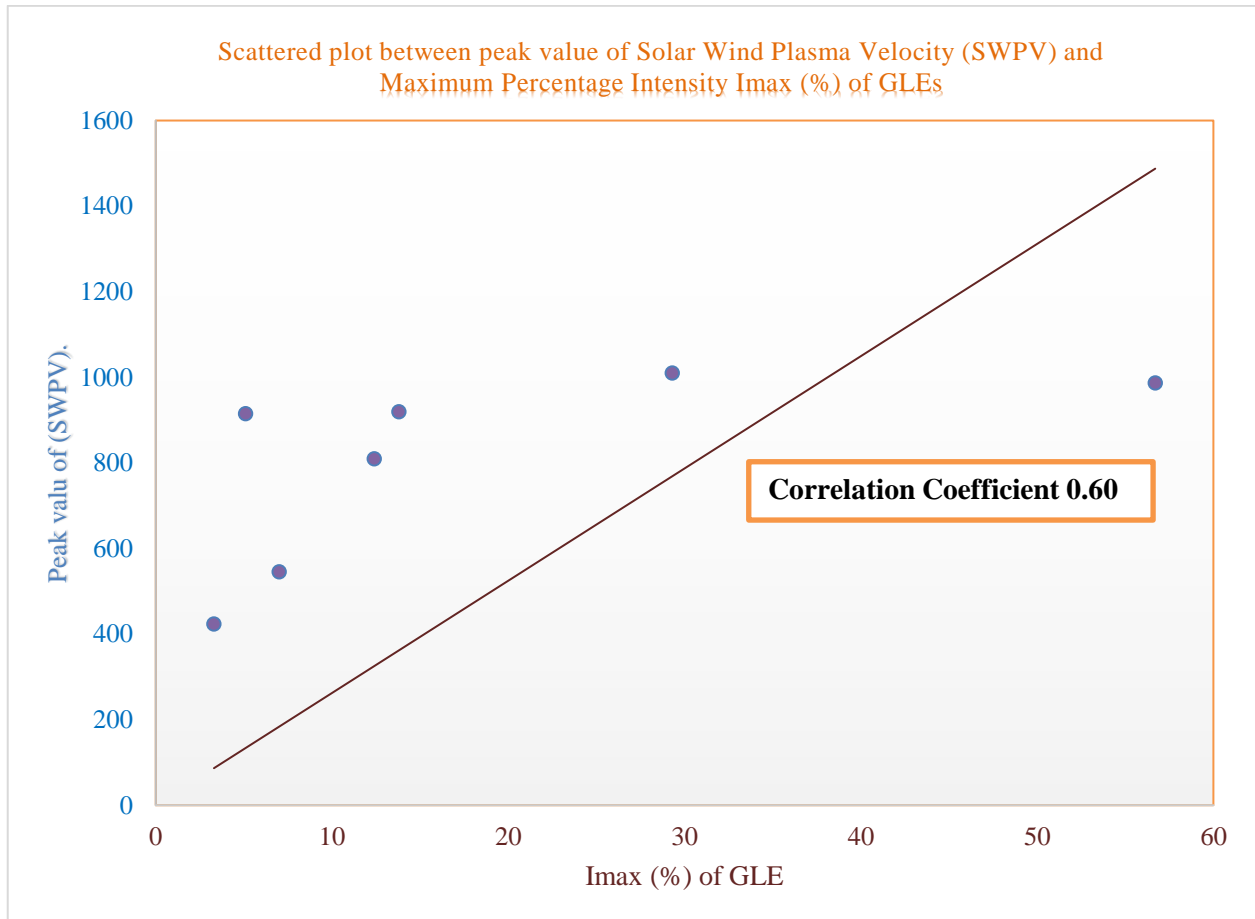


Figure 7- Scattered plot between peak value of solar Wind Plasma Velocity (SWPV) and maximum percentage intensity I_{max} (%) of GLEs.

5.2 Correlation with Magnitude of Associated SWPV Disturbances

To know the statistical behavior of maximum percentage intensity of GLEs with magnitude of associated disturbances in solar wind plasma velocity we have plotted a bar diagram of maximum percentage intensity of GLEs and magnitude of associated disturbances in solar wind plasma velocity in figure 5, and scatter plot between maximum percentage intensity of GLEs and peak value of associated disturbances in solar wind plasma velocity in figure 6. From the figure 5 it is inferred that, most of GLEs events having higher maximum percentage intensity I_{max} (%) are associated with such SWV disturbances which have relatively higher magnitude but these two events do not have any fixed proportion, We have found some GLE events which have higher maximum percentage intensity but they are associated with such SWV disturbances which have relatively lower magnitude and vice versa .From the trend line of the scatter plot, it may be inferred that there is positive correlation between maximum percentage intensity of GLEs and magnitude of associated disturbances of SWV disturbances .Positive correlation has been found between maximum percentage intensity of GLEs and magnitude of SWV disturbances. Statistically calculated co-relation co-efficient is 0.39 between these two events.

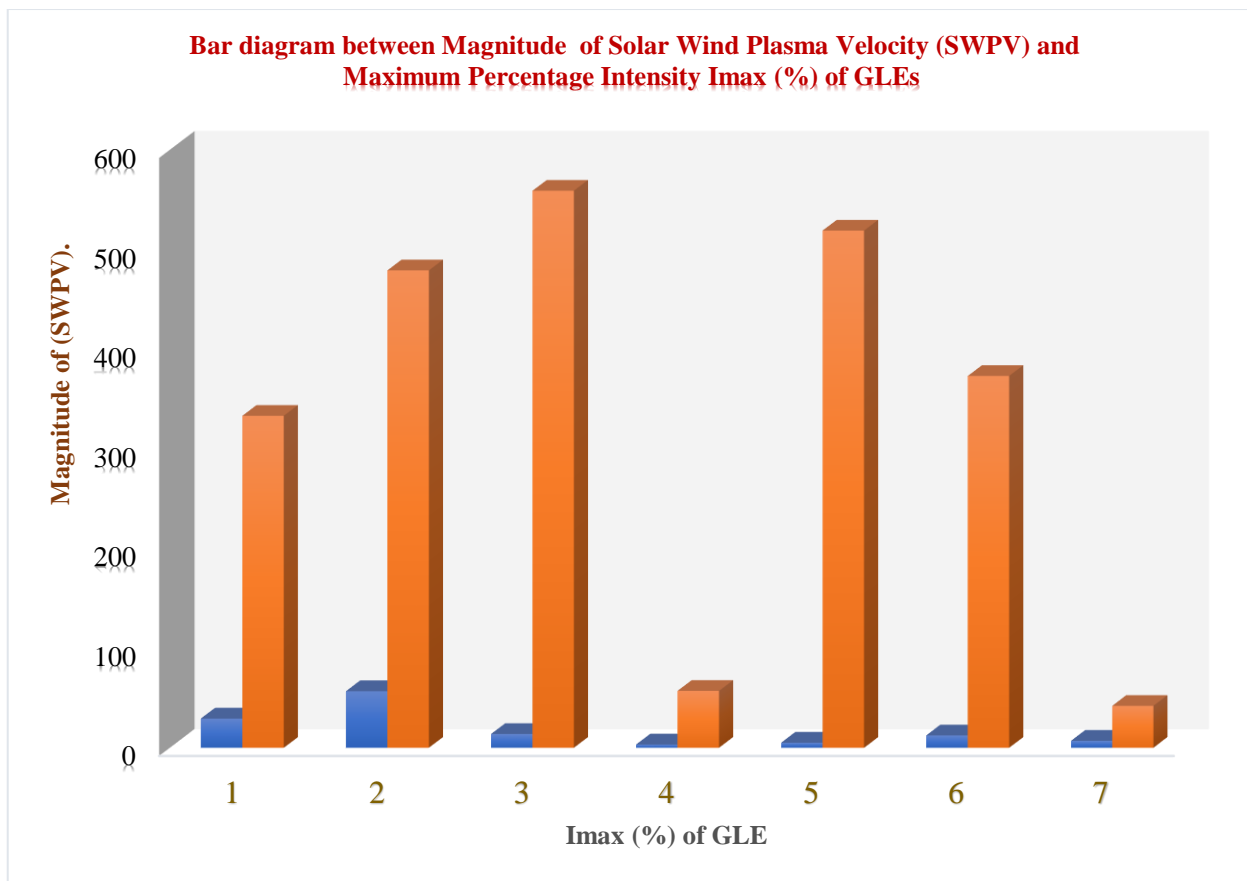


Figure-8 Bar diagram between Magnitude of Solar Wind Plasma Velocity (SWPV) and Maximum Percentage Intensity I_{max} (%) of GLEs.

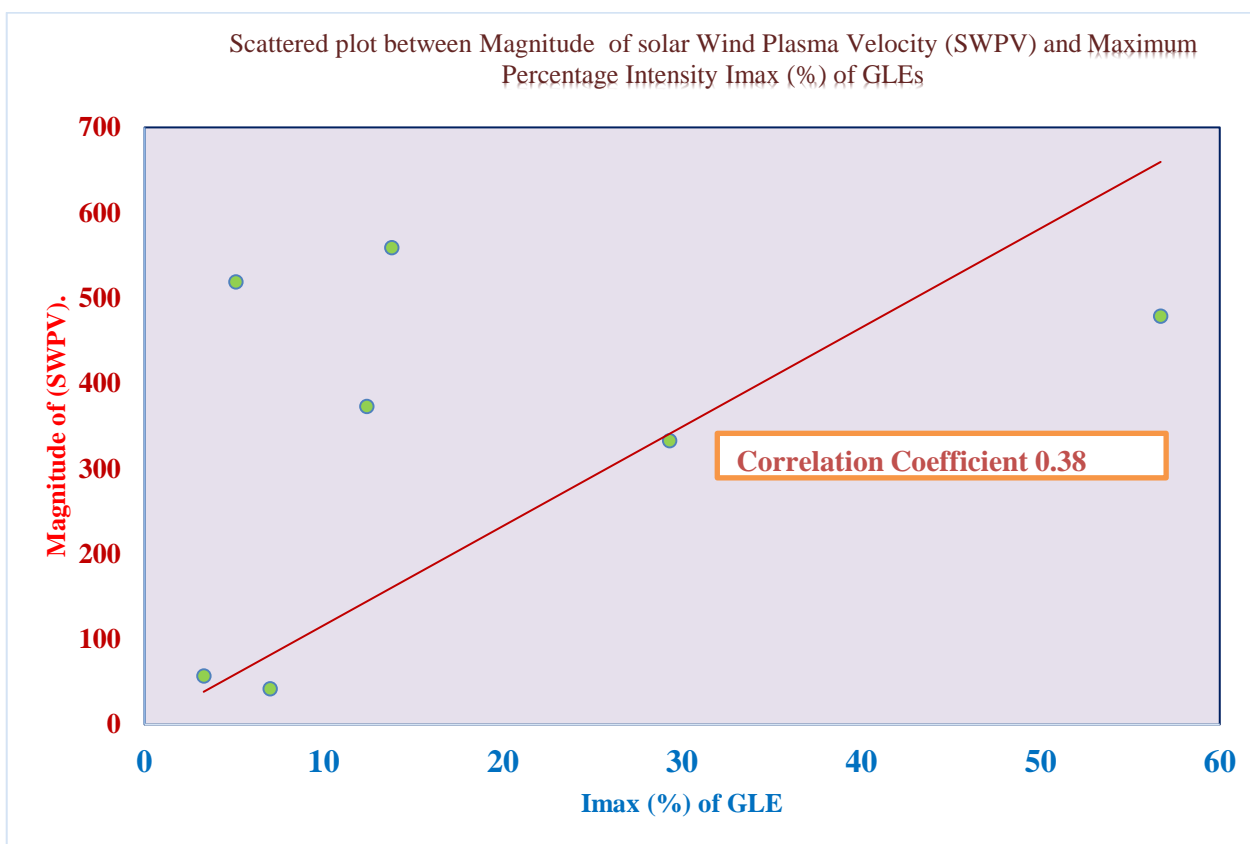


Figure-9 Scattered plot between Magnitude of Solar Wind Plasma Velocity (SWPV) and Maximum Percentage Intensity I_{max} (%) of GLEs.

6. Ground Level Enhancements in Relation with Solar Wind Plasma Pressure

We studied the Ground Level Enhancement (GLEs) observed during the period of near solar maximum of solar cycle of 23 with disturbances in solar wind plasma pressure. The observed GLEs and associated disturbances in solar wind plasma pressure are listed in Table. From the data analysis of the table, it is observed that we have 09 GLEs in which the data of SWPP is not available for association of 02 GLE; all 08 GLEs have been found to be associated with disturbances in solar wind plasma pressure (SWPP).

6.1 Correlation with Peak Value of SWPP Disturbances

To know the statistical behavior of maximum percentage intensity of GLEs with peak value of associated disturbances in solar wind plasma pressure we have plotted a bar diagram of maximum percentage intensity of GLEs and peak value of associated disturbances in solar wind plasma pressure in figure 9, and scatter plot between maximum percentage intensity of GLEs and peak value of associated disturbances in solar wind plasma pressure in figure 10. From the figure 9 it is inferred that, most of GLEs events having higher maximum percentage intensity I_{max} (%) are associated with such SWPP disturbances which have relatively higher peak value but these two events do not have any fixed proportion, We have found some GLE events which have higher maximum percentage intensity but they are associated with such SWP disturbances which have relatively lower peak values and vice versa. From the trend line of the scatter plot, it may be inferred that there is large positive correlation between maximum percentage intensity of GLEs and peak value of associated disturbances of SWPP disturbances. Positive correlation has been found between maximum percentage intensity of GLEs and peak value of SWV disturbances. Statistically calculated co-relation co-efficient is 0.87 between these two events.

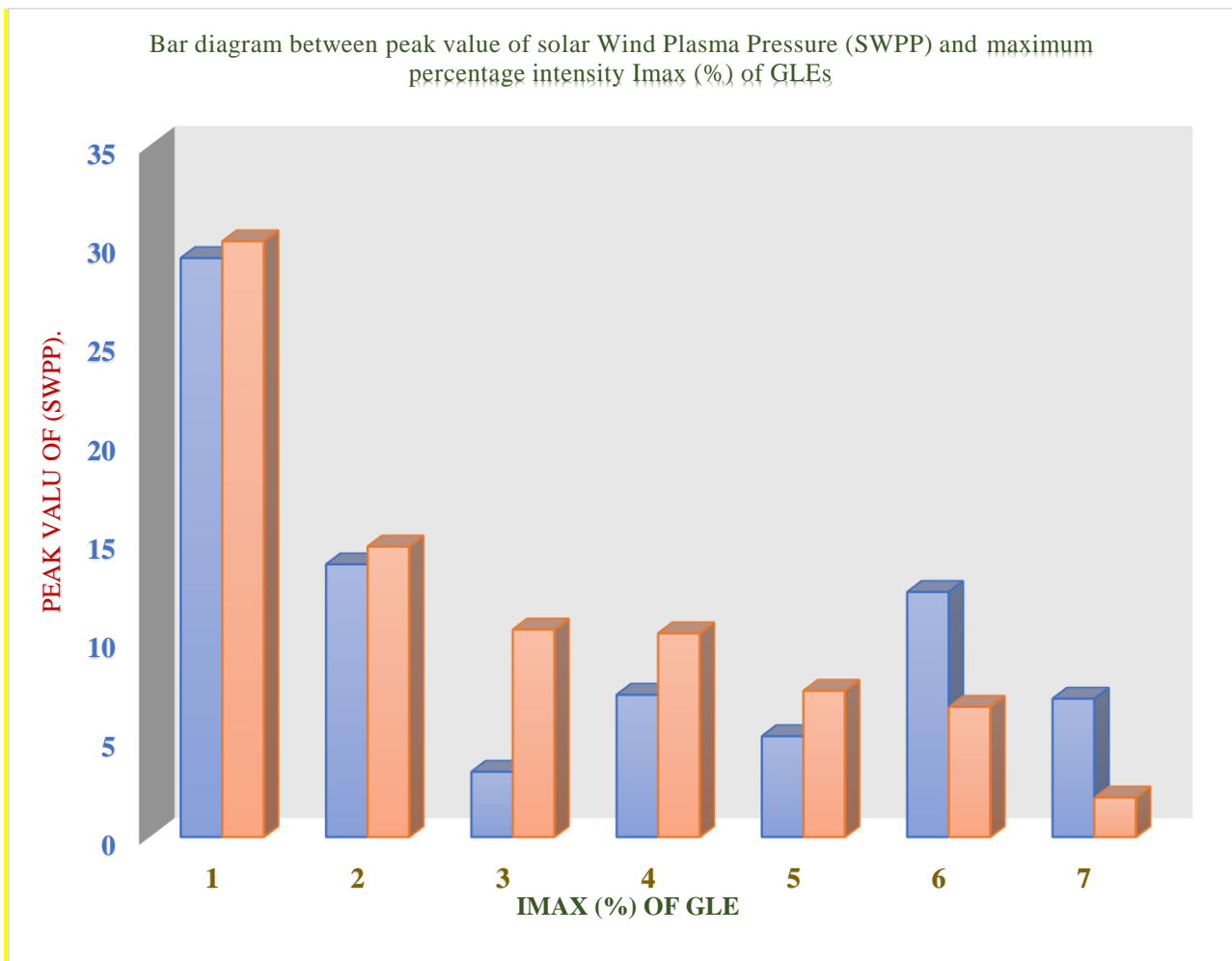


Figure- 10 Bar diagram between peak value of solar Wind Plasma Pressure (SWPP) and maximum percentage intensity I_{max} (%) of GLEs.

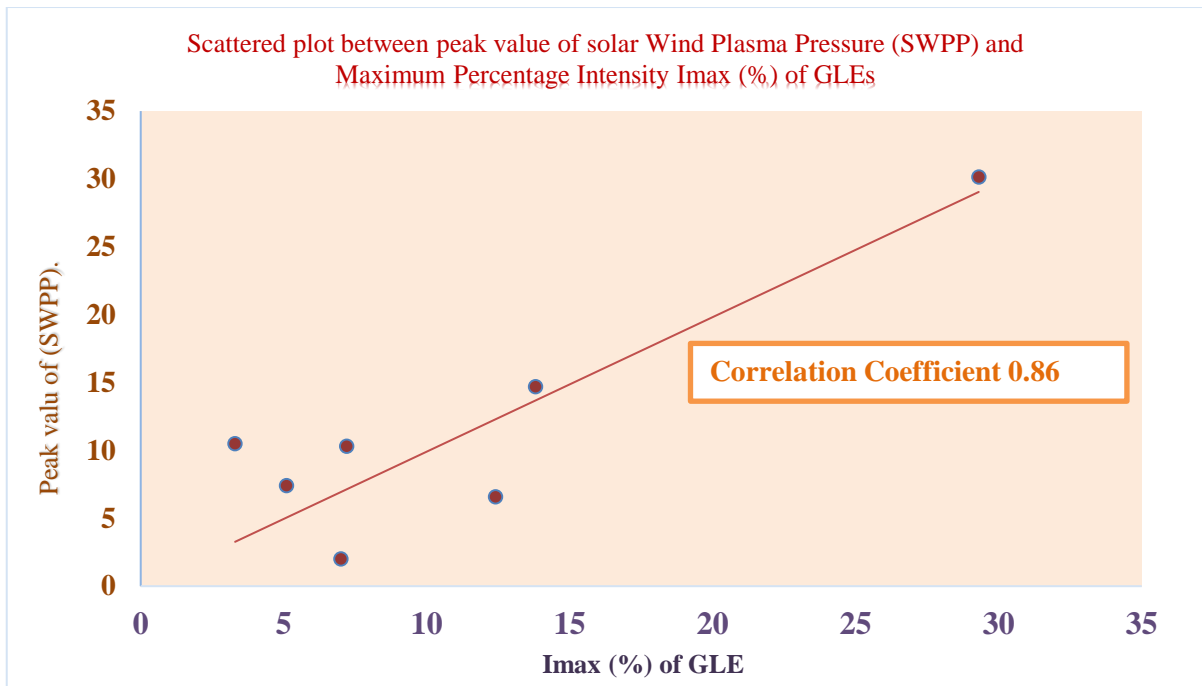


Figure-11 Scattered plot between peak value of Solar Wind Plasma Pressure (SWPP) and Maximum Percentage Intensity Imax (%) of GLEs.

6.2 Correlation with Magnitude of Associated SWPP Disturbances

To know the statistical behavior of maximum percentage intensity of GLEs with magnitude of associated disturbances in solar wind plasma pressure we have plotted a bar diagram of maximum percentage intensity of GLEs and magnitude of associated disturbances in solar wind plasma pressure in figure 11, and scatter plot between maximum percentage intensity of GLEs and magnitude of associated disturbances in solar wind plasma pressure in figure 12. From the figure 11 it is inferred that, most of GLEs events having higher maximum percentage intensity Imax (%) are associated with such SWP disturbances which have relatively higher magnitude but these two events do not have any fixed proportion, We have found some GLE events which have higher maximum percentage intensity but they are associated with such SWP disturbances which have relatively lower magnitude and vice versa. From the trend line of the scatter plot, it may be inferred that there is large positive correlation between maximum percentage intensity of GLEs and magnitude of associated disturbances of SWP disturbances. Positive correlation has been found between maximum percentage intensity of GLEs and peak value of SWP disturbances. Statistically calculated co-relation co-efficient is 0.83 between these two events.

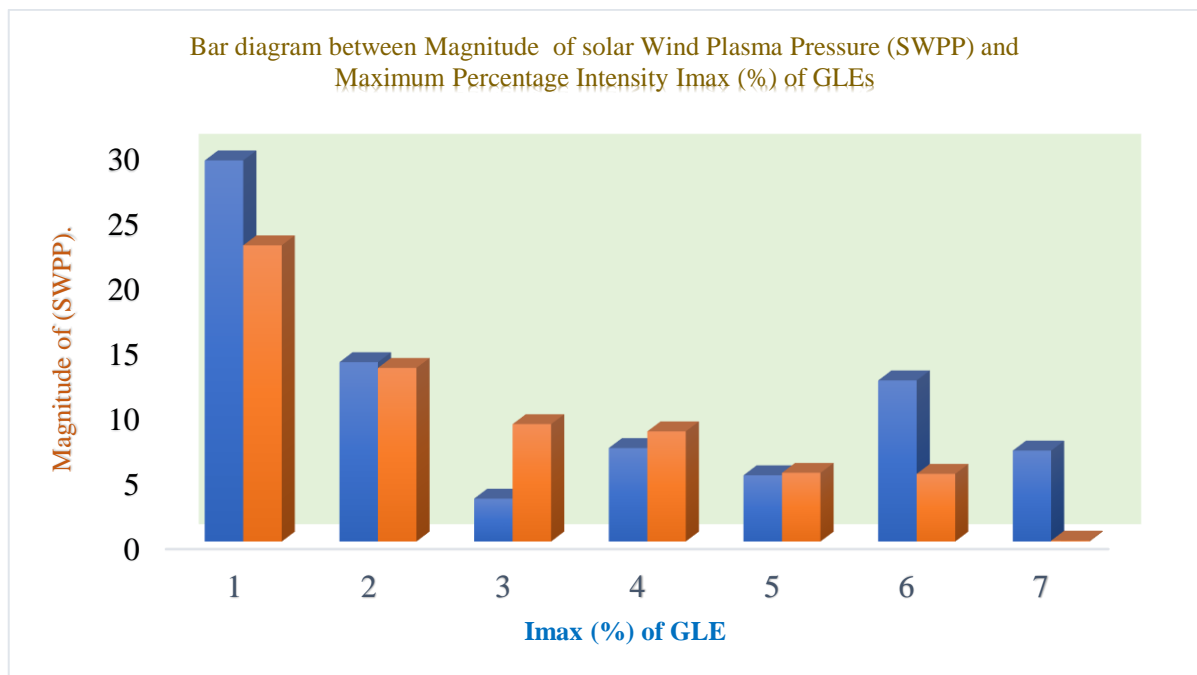


Figure-12 Bar diagram between Magnitude of solar Wind Plasma Pressure (SWPP) and Maximum Percentage Intensity Imax (%) of GLEs.

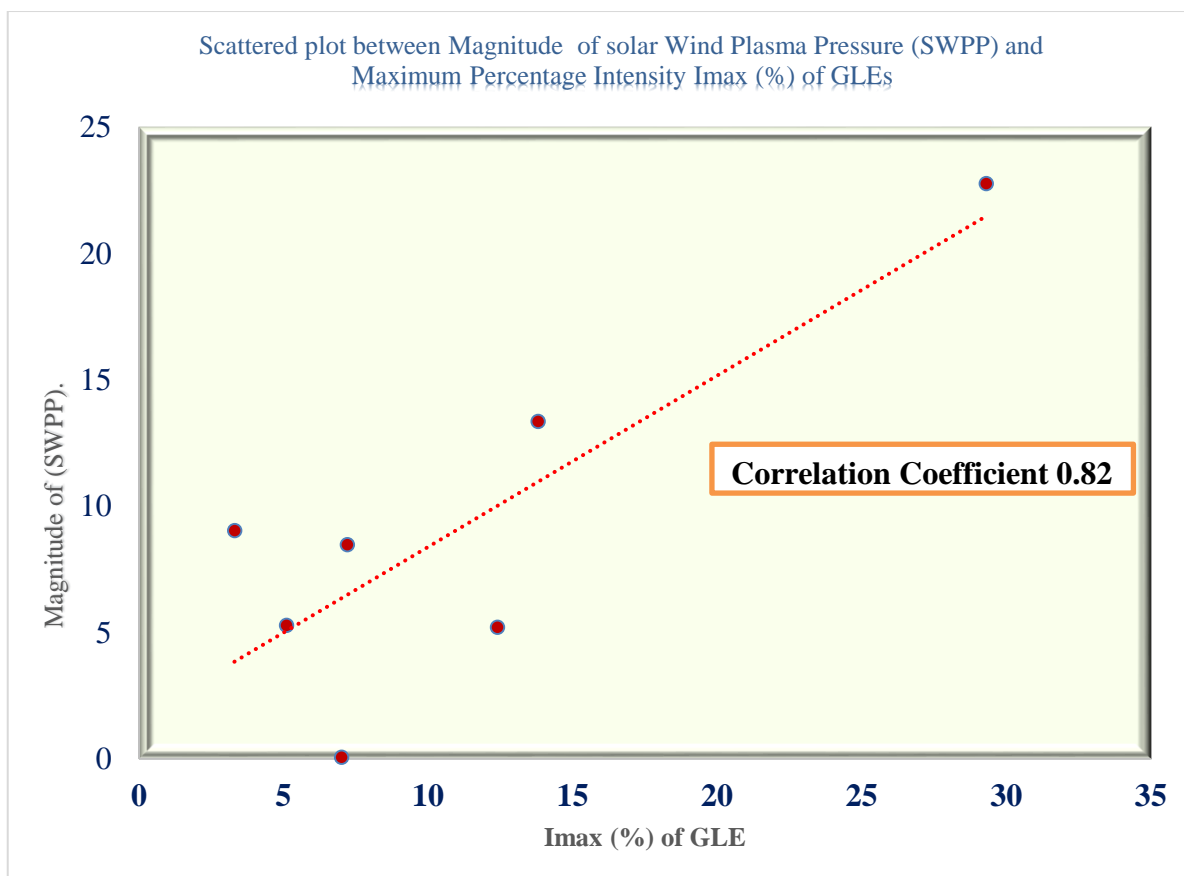


Figure-13 Scattered plot between Magnitude of solar Wind Plasma Pressure (SWPP) and Maximum Percentage Intensity I_{max} (%) of GLEs.

7. Results and Conclusion

7.1 Main Results

In this paper we have explained the ground level enhancement with coronal mass ejections solar flares and disturbances in solar wind plasma parameters during the period of near solar cycle 23 (2000-2003). The results are summarized as follows. All the GLEs are associated with X-Class X ray solar flares and GLE-associated flares originated from the western hemisphere of the Sun.

All the GLEs associated with strong flares were also associated with fast CMEs with minimum speed 834 Km/S and maximum speed 2465 Km/S. On the average, the speed(1840 km/s) of GLE-associated CMEs is much faster than the speed (423.39 km/s) of non-GLE-associated.

Positive correlation with correlation coefficient 0.43 has been determined between maximum percentage intensity of GLE and peak value of associated disturbances in IMF.

Positive correlation with correlation coefficient 0.31 has been determined between maximum percentage intensity of GLE and magnitude of associated disturbances in IMF.

Large positive correlation with correlation coefficient 0.61 has been determined, between percentage intensity of GLEs and peak value of associated disturbances in solar wind plasma velocity.

Positive correlation with correlation coefficient 0.39 has been determined between maximum percentage intensity of GLE and magnitude of associated disturbances in solar wind plasma velocity.

Large positive correlation with correlation coefficient 0.87 has been determined between percentage intensity of GLEs and peak value of associated disturbances in solar wind plasma pressure

Large positive correlation with correlation coefficient 0.83 between percentage intensity of GLEs and magnitude of associated disturbances in solar wind plasma pressure.

8. Conclusions

It is well known that energetic particle fluxes having strong fluctuations are very much necessary for causing GLEs. Since a solar flare and coronal mass ejections are violent explosion of solar energetic particles so hard X-Ray solar flares associated with fast coronal mass ejections may also cause GLE. Further strong positive correlation with solar wind plasma velocity and solar wind plasma pressure may play fundamental role to cause GLEs.

Conflict of Interest

The authors declare that there is no conflict in this manuscript.

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