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GROUND LEVEL ENHANCEMENTS IN RELATION WITH ENERGETIC SOLAR FEATURES AND DISTURBANCES IN SOLAR WIND PLASMA PARAMETERS

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ABSTRACT

Ground Level Enhancements (GLEs) in cosmic ray intensity observed during the period of 1997–2012 have been studied with energetic solar features and disturbances in solar wind plasma parameters and it is seen that all the GLEs have been found to be associated with coronal mass ejections, hard X-ray solar flares and solar radio bursts. All the GLEs have also been found to be associated with sudden jumps in solar proton flux of energy of $\geq$ 60 Mev. A positive correlation with correlation coefficient of 0.48 has been found between the maximum percentage intensity (Imax%) of Ground Level Enhancements and the peak value of solar proton flux of energy ($\geq$ 60Mev). All the Ground Level Enhancements have been found to be associated with jumps in solar wind plasma velocity (JSWV) events. A positive correlation with correlation coefficient of 0.43 has been found between the maximum percentage intensity (Imax %) of Ground Level Enhancements and the peak value of solar wind plasma velocity of associated (JSWV) events. All the Ground Level Enhancements have been found to be associated with jumps in solar wind plasma pressure (JSWP) events. A positive correlation with correlation coefficient of 0.67 has been found between the maximum percentage intensity (Imax %) of Ground Level Enhancements and the peak value of solar wind plasma pressure of associated (JSWP) events and of 0.68 between the maximum percentage intensity (Imax %) of Ground Level Enhancements and the magnitude of the jump in solar wind plasma pressure of associated (JSWP) events.

Key words: Disturbances in Solar Wind Plasma Parameters: Coronal Mass Ejections: X-Ray Solar Flares: Radio Bursts: Ground Level Enhancements and solar proton flux.

1. INTRODUCTION

Ground Level Enhancements (GLEs) 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. Ground Level Enhancements have been studied by several scientists with different solar interplanetary parameters to explain the origin, causes and characteristics of GLE (Meyer et al., 1956; Park, 1957; Dorman & Venkatesan, 1993; Kudela et al., 1993; Reames, 1995; Miroshnichenko, 2001; Duldig, 2001; Smart & Shea, 2002; Cliver et al., 2004; Gopalswamy et al., 2005; Kudela et al., 1993; Reames, 1999, 2009; Gopalswamy et al., 2010). Oh et al. (2010) have studied Ground Level Enhancements with solar proton events and found that solar proton events associated with Ground Level Enhancements have well-defined profiles with a large increase and clear peak for each proton channel. They have larger peak intensities and shorter delay times between onset and peak than solar proton events without Ground Level Enhancements. Fluences and peak intensities of solar proton events have a good correlation with percent increases of Ground Level Enhancements. Firoz et al. (2010) have studied Ground Level Enhancements, observed for the period from 1979–2009, and characteristics of the 32 event - associated solar flares, coronal mass ejections and solar energetic particle fluxes have been analyzed. They have found that all of the 32 Ground Level Enhancements are associated with solar flares, coronal mass ejections and solar energetic particle fluxes. Approximately 82% of the events have been found to be associated with X-class flares. The average speed (1726.17 km/s) of GLE-associated CMEs is much faster than the average speed (423.39 km/s) of non GLE-associated CMEs. Smart et al. (2006) have studied Ground Level Enhancements with coronal mass ejections and reported that although Ground Level Enhancements are usually associated with fast CMEs, the peak of the GLE depends on its speed and position angle. Firoz et al. (2010) have investigated the relationship of Ground Level Enhancements with simultaneous solar, interplanetary and geophysical parameters, for the period of 1996–2006. They have concluded that the total interplanetary magnetic field (IMF-Btot) transported by the solar wind from the sun may sometimes cause sudden increases in cosmic ray intensity.They have found a positive correlation between solar wind plasma velocities (Vsw km/s) and GLE peaks. Gopalswamy (2008; 2010) have analyzed the Ground Level Enhancement events of cycle 23, and concluded that all the Ground Level Enhancements have been found to be associated with coronal mass ejections. The occurrence rate of Ground Level Enhancements have been found to be $\sim$ 1.5 per year. The number of Ground Level Enhancements events does not follow the solar cycle, but steadily increases from the minimum to the declining phases. In the present paper, Ground Level Enhancements observed during the period of 1997–2012 have been analyzed with coronal mass ejections, radio bursts, solar proton fluxes and disturbances in solar wind plasma parameters to determine which of the solar and interplanetary parameters possibly generate Ground Level Enhancements.

2. EXPERIMENTAL DATA

In this study, Ground Level Enhancements have been studied with coronal mass ejections, radio bursts, X-ray solar flares and disturbances in solar wind plasma parameters observed during the period of 1997–2012. The data for GLEs have been taken from Oulu super neutron monitor. The data for solar proton flux and disturbances in solar wind plasma parameters, solar wind plasma velocity, and pressure have been taken from omni web data (http://omniweb.gsfc.nasa.gov/form/dxi.html). The data for 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 for solar radio bursts and X-ray solar flares are taken from STP solar data (http://www.ngdc.noaa.gov/stp/solar/solardataservices .html).

3. DATA ANALYSIS AND RESULTS

From the data analysis of Ground Level Enhancements, Coronal Mass Ejections, Solar radio bursts and X-ray solar flares listed in Table 1, we have found that all the Ground Level Enhancements (GLEs) are associated with coronal mass ejections (CMEs).

The association rates of halo and partial halo coronal mass ejections have been found to be 88.23% and 11.76% respectively. All the GLEs have been found to be associated with X-ray solar flares and the associated solar flares are X-Class and M-Class X-ray solar flares. The association rates of X-Class and M-Class X-ray solar flares are 88.23% and 11.76% respectively. Furthermore, all the Ground Level Enhancements are associated with type II and Type III radio bursts.

From the data analysis of GLEs observed during the period of 1997–2012 with solar proton fluxes of energy $\geq$ 60Mev listed in Table 1, it is observed that all the GLEs have been found to be associated with a sudden rise in solar proton flux of energy $\geq$ 60Mev. We have 17 GLEs in our list for which we have no data for solar proton flux. Of 14 GLEs, all are associated with a sudden rise in solar proton flux of energy $\geq$ 60Mev.

To determine the statistical behavior of GLEs with peak fluxes of solar proton events a scatter plot has been plotted between the maximum percentage intensity Imax (%) of GLEs and the peak flux of solar proton events and the resulting plot is shown in Figure 1. From this Figure it is inferred that most GLE events having higher maximum percentage intensity (Imax %) are associated with solar proton events which have relatively high peak flux but there is scatter. We have found some GLE events which have higher maximum percentage intensity (Imax %) but are associated with solar proton events which have relatively low peak flux.

From the scatter plot (Figure 1), it may be inferred that there is moderate positive correlation between the maximum percentage intensity of GLEs and the peak flux of associated solar proton events. A positive correlation has been found between the maximum percentage intensity of GLEs and the peak flux of solar proton events. The calculated correlation coefficient is 0.48 between these two events.

From the data analysis of GLEs and associated disturbances in solar wind plasma velocity listed in Table 2, it is observed all the GLEs have been found to be associated with disturbances in solar wind plasma velocity. We have 17 GLEs for which we have no data for JSWV events. The available data for JSWV events for association is for 15 GLEs events. Of 15, all the GLEs (100%) are associated with jumps in solar wind plasma velocity.

To determine the statistical behavior of GLEs with peak value of associated JSWV events a scatter plot has been plotted between the maximum percentage intensity (Imax %) of GLEs and the peak value of velocity of associated JSWV events and the resulting plot is shown in Figure 2. From this Figure it is inferred that most of GLEs events having higher maximum percentage intensity (Imax %) are associated with JSWV which have relatively high peak velocity but there is scatter. We have found some GLEs events which have higher value of maximum percentage intensity (Imax %) but are associated with JSWV events which have lower values of peak velocity and vice versa. A positive correlation has been found between the maximum percentage intensity of GLEs and the peak velocity of associated JSWV events. The calculated correlation coefficient is 0.43 between these two events.

From the data analysis of GLEs and associated disturbances in solar wind plasma pressure listed in Table 2, it is observed all the GLEs have been found to be associated with disturbances in solar wind plasma pressure. We have 17 GLEs for which we have no data for JSWP events. The available data for JSWP events for association is for 15 GLEs events. Of 15m all the GLEs (100%) are associated with jumps in solar wind plasma

Table 1
GLEs, Associated Solar Features and Solar Proton Flux

	Ground Level Enhancements			Solar Radio Bursts				CMEs		
S.N.	GLE event Date	GLE Onset (Obs)	GLE int(%)	Type II Onset	End time	Type III Onset	Flare Class /Location	CME Type	CMEs Speed(km/s)	≥60Mev
1	1997Nov06	12:10	11.3	11:53	8:30	11:52	X9.4/S18W63	H	785	110
2	1998May02	13:55	6.8	13:41	14:50	13:35	X1.1S15W15	H	657	15.1
3	1998May06	8:25	4.2	8:03	8:35	8:01	X2.7/S11W65	P	675	14.2
4	1998Aug24	22:50	3.3	22:02	6:20	22:04	X1.0/N35E09	H	2066	11
5	2000Jul14	10:30	29.3	10:28	14:30	10:18	X5.7/N22W07	H	1078	1200
6	2001Apr15	14:00	56.7	13:47	13:00	13:49	X14/S20W85	P	834	203
7	2001Apr18	2:35	13.8	2:17	14:00	2:15	?/S23W117	H	2465	22.2
8	2001Nov04	17:00	3.3	16:10	11:00	16:13	X1.0/N06W18	H	1810	Nd
9	2001Dec26	5:30	7.2	5:12	5:00	5:13	M7.1/N08W54	H	1785	Nd
10	2002Aug24	1:18	5.1	1:01	3:25	1:01	X3.1/S02W81	H	2066	43.3
11	2003Oct28	11:22	12.4	11:02	24:00:00	11:03	X17/S20E02	H	2459	Nd
12	2003Oct29	21:30	8.1	20:42	24:00:00	20:41	X10/S19W09	H	2029	902
13	2003Nov02	17:30	7	17:14	1:00	17:16	X8.3/S18W59	H	2036	105
14	2005Jan17	9:55	3	9:43	16:00	9:41	X3.8/N14W25	H	2547	255
15	2005Jan20	6:51	277.3	6:44	16:30	6:45	X7.1/N14W61	H	940	956
16	2006Dec13	2:45	92.3	2:26	10:40	2:24	X3.4/S06W23	H	1774	179
17	2012May17	1:43	16	1:31	1:44	1:31	M5.1/N11W76	H	1582	43.24

Table 2
Ground Level Enhancements and Associated Disturbances in Solar Wind Plasma Parameters

	Ground Level Enhancements			Solar Wind Plasma Velocity			Solar Wind Plsma Pressure			
S.N.t	GLE event Date	GLE Onset (Obs)	GLE int(%)	Start time in dd(hh)	maximum jump time in dd(hh)	Maximum velocity in Km/s	Start time in dd(hh)	maximum jump time in dd(hh)	Maximum Pressure npa	Magnitude
1	1997Nov06	12:10	11.3	06(18)	07(03)	559	06(17)	06(23)	8.94	7.19
2	1998May02	13:55	6.8	01(20)	02(04)	638	01(21)	01(23)	10.11	7.89
3	1998May06	8:25	4.2	05(00)	05(03)	640	05(00)	05(03)	2.74	1.24
4	1998Aug24	22:50	3.3	25(02)	25(19)	426	24(21)	24(22)	2	0.5
5	2000Jul14	10:30	29.3	15(10)	15(16)	1010	15(12)	15(14)	30.15	22.78
6	2001Apr15	14:00	56.7	15(19)	15(22)	987	Nd	Nd	Nd	Nd
7	2001Apr18	2:35	13.8	18(00)	18(06)	919	18(00)	18(05)	14.7	13.36
8	2001Nov04	17:00	3.3	05(04)	05(19)	423	05(06)	05(14)	10.5	9.04
9	2001Dec26	5:30	7.2	Nd	Nd	Nd	26(00)	26(05)	10.31	8.48
10	2002Aug24	1:18	5.1	23(06)	23(18)	915	23(00)	23(11)	7.4	5.29
11	2003Oct28	11:22	12.4	27(21)	28(13)	809	28(01)	28(08)	6.59	5.21
12	2003Oct29	21:30	8.1	Nd	Nd	Nd	Nd	Nd	Nd	Nd
13	2003Nov02	17:30	7	03(02)	03(22)	545	01(05)	01(14)	2	0.07
14	2005Jan17	9:55	3	17(02)	17(13)	798	17(10)	17(16)	58.22	53.72
15	2005Jan20	6:51	277.3	21(15)	21(19)	950	21(16)	21(19)	62.45	60.17
16	2006Dec13	2:45	92.3	14(11)	14(15)	955	14(13)	14(18)	17.51	16.51
17	2012May17	1:43	16	17(12)	18(07)	406	17(15)	17(20)	2.45	0.69

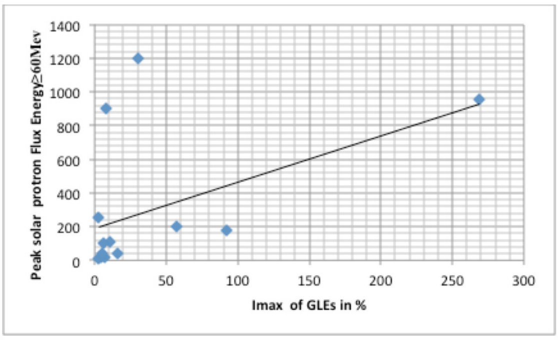

Figure 1. Shows scatter plot between the maximum percentage intensity (Imax %) of GLEs and the peak solar proton flux showing a positive correlation with correlation coefficient 0.48

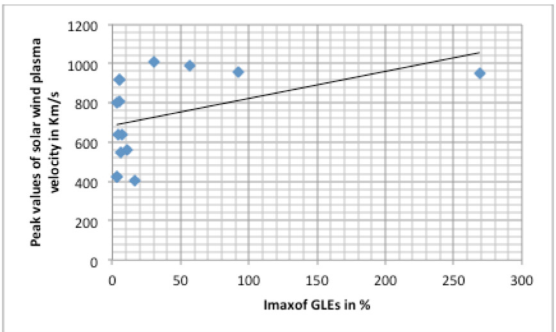

Figure 2. Shows scatter plot between the maximum percentage intensity (Imax %) of GLEs and the peak value of solar wind plasma velocity showing a positive correlation with correlation coefficient 0.43

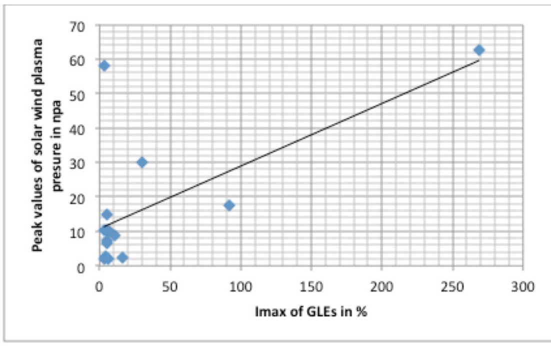

Figure 3. Shows scatter plot between the maximum percentage intensity (Imax %) of GLEs and the peak value of solar wind plasma pressure showing a positive correlation with correlation coefficient 0.67

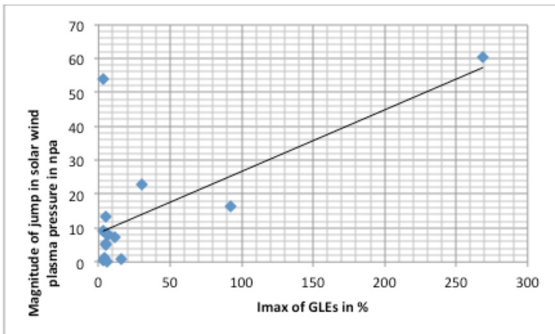

Figure 4. Shows scatter plot between the maximum percentage intensity (Imax %)of GLEs and the magnitude of jumps in solar wind plasma pressure showing a positive correlation with correlation coefficient 0.68

pressure.

To determine the statistical behavior of GLEs with the peak value of associated JSWP events a scatter plot has been plotted between the maximum percentage intensity (Imax %) of GLEs and the peak value of pressure of associated JSWP events and the resulting plot is shown in Figure 3. From this Figure it is inferred that most of GLEs events having higher maximum percentage intensity Imax (%) are associated with JSWP events which have relatively high peak pressure but there is scatter. We have found some GLEs events which have higher values of maximum percentage intensity (Imax %) but are associated with JSWP events which have lower values of peak pressure and vice versa. A positive correlation has been found between the maximum percentage intensity of GLEs and the peak pressure of associated JSWP events. The calculated correlation coefficient is 0.67 between these two events.

To determine the statistical behavior of GLEs with the magnitude of the jump of associated JSWP events a scatter plot has been plotted between the maximum percentage intensity (Imax %) of GLEs and the magnitude of the jump of pressure of associated JSWP events and the resulting plot is shown in Figure 4. From this Figure it is inferred that most GLE events having higher maximum percentage intensity (Imax %) are associated with JSWP which have relatively high pressure but there is scatter. We have found some GLEs events which have higher value of maximum percentage intensity (Imax %) but are associated with JSWP events which have lower values of pressure and vice versa. A positive correlation has been found between the maximum percentage intensity of GLEs and the peak pressure of associated JSWP events. The calculated correlation coefficient is 0.68 between these two events.

4. MAIN RESULTS

1-All the Ground Level Enhancements (GLEs) have been found to be associated with halo and partial halo coronal mass ejections (CMEs). The association rates of halo and partial halo coronal mass ejections have been found to be 88.23% and 11.76% respectively.

2-All the GLEs have been found to be associated with X-ray solar flares and the associated solar flares are X-Class and M-Class X-ray solar flares. The association rates of X-Class and M-Class X-ray solar flares are found to be 88.23% and 11.76% respectively.

3-All the Ground Level Enhancements are associated with type II and Type III radio bursts.

4-All the GLEs have been found to be associated with a sudden rise in solar proton flux of energy $\geq$

60Mev

5-A positive correlation has been found between the maximum percentage intensity of GLEs and the peak flux of solar proton events. The calculated correlation coefficient is 0.48 between these two events.

6-All the GLEs have been found to be associated with disturbances in solar wind plasma velocity.

7-A positive correlation has been found between the maximum percentage intensity of GLEs and the peak velocity of associated JSWV events. The calculated correlation coefficient is 0.43 between these two events.

8-All the GLEs have been found to be associated with disturbances in solar wind plasma pressure.

9-A positive correlation has been found between the maximum percentage intensity of GLEs and the peak pressure of associated JSWP events. The calculated correlation coefficient is 0.67 between these two events.

10-A positive correlation has been found between the maximum percentage intensity of GLEs and the peak pressure of associated JSWP events. The calculated correlation coefficient is 0.68 between these two events.

5. CONCLUSIONS

In our study all the GLEs have been found to be associated with coronal mass ejections, X-ray solar flares, solar radio bursts, sudden jumps in solar proton flux of energy ≥ 60 Mev, and jumps in solar wind plasma velocity and pressure. A positive correlation with correlation coefficient of 0.48 has been found between the maximum percentage intensity (Imax%) of Ground Level Enhancements and the peak value of solar proton flux of energy ($\geq$ 60Mev). A positive correlation with correlation coefficient of 0.43 has been found between the maximum percentage intensity (Imax%) of Ground Level Enhancements and the peak value of the solar wind plasma velocity of associated (JSWV) events.

A positive correlation with correlation coefficient of 0.67 has been found between the maximum percentage intensity (Imax %) of Ground Level Enhancements and the peak value of the solar wind plasma pressure of associated (JSWP) events and of 0.68 between the maximum percentage intensity (Imax %) of Ground Level Enhancements and the magnitude of jumps in the solar wind plasma pressure of associated (JSWP) events. These results show that Ground Level Enhancements are strongly related to coronal mass ejections, X-ray solar flares, solar radio bursts, solar proton flux and disturbances in solar wind plasma velocity and pressure.

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