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Study of Ground level Enhancement Associated with Solar Output During 2009 to 2021

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***Abstract*— Ground-level enhancements (GLEs) are sudden, sharp, and short-lived increases in cosmic ray intensities registered by neutron monitors (NM). These enhancements are known to take place during powerful solar eruptions. In the present investigation, the cosmic ray intensities registered by the Oulu neutron monitor have been studied for the period between January 2009 and October 2021. Over this span of time, increase rates of 3 GLEs have been deduced. In addition, we have studied characteristics of the 3 events associated solar flares, coronal mass ejections (CMEs), and solar energetic particle (SEP) fluxes. We found that all of the 3 GLEs were associated with strong solar flares (GLE 71 associated with class M and GLE 72 &GLE 73 associated with class X), CMEs, and SEP fluxes. GLE-associated CMEs was much faster than the average speed of non-GLE-associated CMEs. Although a GLE event is often associated with a fast CME, this alone does not necessarily cause the enhancement. Solar flares with strong optical signatures may sometimes cause GLE. High SEP fluxes often seem to be responsible for causing GLEs as the correlation with SEP fluxes implies.**

***Index Terms*— Ground Level Enhancement Coronal Mass Ejection Solar Flare Solar Energetic Particle**

I. INTRODUCTION

Cosmic rays are high-energy particles originate from different sources such as remnants of supernovae, neutron stars, black holes, objects in radio galaxies, and sometimes events in our Sun and its heliosphere [e.g., Hillas,1972; Gaisser, 1990; Longair, 1992; Firoz et al., 2009]. Ground level enhancements (GLEs) are increases of cosmic ray intensity measured on the Earth's ground. Solar energetic particles (SEPs), solar flares, and/or coronal mass ejections (CMEs) are also normally observed when GLEs occur, suggesting that these are causing GLEs or are caused by the same process in the Sun or its corona. SEPs, solar flares, and CMEs are produced in sporadic solar eruptions. Solar flares and CMEs are in the larger ones. The distinction between solar flare and CME is that a solar flare is a sudden flash of electromagnetic radiation, whereas a CME is a mass motion in the solar corona that can be seen in a coronagraph. The spatial relation between flares and CMEs depends on the magnetic field configurations involved in the solar eruption process. Flares are perhaps photospheric and CMEs are chromospheric. The flares erupt from the intensely luminous area of the Sun, whereas the CMEs are ejected from an incandescent and transparent layer of gas lying above and surrounding the photosphere. So, flares can presumably trigger CMEs. However, there are also arguments that both phenomena might originate from the same active region of the solar disk even though they have different manifestations. Detailed explanations can be found in several studies [e.g.,Kahler et al., 1978;Cliver et al., 1982;Dorman, 2004;Yashiro et al., 2008;Belov,2009] The solar energetic particles having intense fluxes in near Earth space are of great interest, in particular, because of their impacts on cosmic ray modulation. Those particles spread near the Sun and are carried away by CME-driven shock waves propagating through the interplanetary space. The propagation process may accelerate particles to higher energies that intensify the cosmic ray intensity to a sharp increase. Once the acceleration of particles ends, the sharp rise of cosmic ray intensity measured at the ground with neutron monitors returns to the background level or close to the background level within tens of minutes to hours. Flare and CME-driven shock reconnection may also cause a sharp rise in the cosmic ray intensity at the Earth. If the particles accelerate to sufficiently high energies (GeV) and the intensity is sufficiently high, then enhancements at the ground (GLEs) are also thought to occur. SEP fluxes at different energy channels can be weighed by their corresponding fluences, which are typically measured by satellites in geostationary orbits. They demonstrated different asymmetry relative to minimum and maximum states of solar activity cycle. SEP fluxes are observed with energy of MeV, whereas GLEs are thought to require a typical energy of gigaelectron volts to be high enough for the particles to penetrate the Earth's atmosphere. [e.g.,Dorman and Venkatesan, 1993;Cliver et al., 2004;Cliver, 2006]. Intense solar flares and fast CMEs consisting of entrained magnetic fields have enough potential to create turmoil in the Earth's atmosphere [e.g.,Manchester et al.,2005;Wang and Wang, 2006]. Namely, electromagnetic emissions produced by solar flares penetrate the Earth's atmosphere and change particle environment on the Earth, consequently disrupting radio transmissions. SEPs that are accelerated at solar eruptive event can propagate to the Earth, causing damage to satellite electronics and posing radiation hazards to astronauts and aircrews [Firoz and Kudela, 2007]. Thus, SEP fluxes, X-ray flares, and CMEs may also cause sharp rises in cosmic ray intensities in the Earth. So, a study on characteristics of GLE-associated SEPs, X-ray flares, can be useful for the understanding of cosmic rays and space weather.

II. DATA AND METHODOLOGY

In this analysis we have used 5-Min and hourly pressure corrected CR count rate data of Oulu NM cut off rigidity 0.8 GV, latitude 65.05^{o} N, longitude 24.47^{o} E (data from http://cosmicrays.oulu.fi) are associated with different solar activity parameters e.g. interplanetary magnetic field B, Bz, are taken from Omniweb(https://omniweb.gsfc.nasa.gov/form/dx1.html),The CME data taken from SOHO LASCO CME catalog (https://cdaw.gsfc.nasa.gov/CME_list/), flare and solar proton event data are taken from NOAA national geophysical data center (https://www.ngdc.noaa.gov/). On these set of data statistics were utilized from January 2009 to October 2021, during the GLE events. This work aims to investigate the Association of several solar interplanetary characteristics to cosmic ray intensity (CRI) during January 2009 to October 2021 using regression trend, correlation coefficient (r) between several solar interplanetary characteristics and cosmic ray intensity (CRI) has been determined.

III. RESULTS AND DISCUSSION

In this paper we investigate the effect of GLE event on solar and interplanetary features during 2009 to 2021 interval when GLE71 amplitude was ~ 15.39% recorded by Oulu neutron monitor station May 17, 2012. We have tracked solar flare and CME events, as well as Interplanetary magnetic field a few days prior to the GLE onset day, in an effort to identify the solar sources causing the event. There was a brief period of initial phase increasing solar activity at the end of May 2012 during the ascending phase of solar cycle 24. Before the day of GLE we found 40 solar flares events on May 14,42 flare events on May 15, On May 16, we found total 40 flares, of which 10 were B-class and 30 were C-class. On May 17, we discovered a total of 40 flares, of which 10 were B-class, 29 were C-class and 1 was M- class the strongest M-class flare (M5.1) of optical importance 1F produced by active NOAA region N11W76 from the set 4 days flare data. This was the first GLE (~15.39%) event of lower mid phase of 24th solar cycle began on May 17, 2012 1:40 UT and peaked 02:05 UT when cosmic ray particles were associated to the solar proton event. The proton fluxes about 255 pfu for energies > 10 MeV was recorded with m-type II and DH-II radio emission. The X-ray flare of class M- (M5.1) of optical importance 1F produced by active NOAA region N11W76, associated with GLE event was began on May 17, 2012 1:40 UT and peaked 02:05 UT and also associated the CME with high-speed of 1582 km/s, on that day SSN equals 110. The abrupt increase in cosmic ray intensity was a hallmark of the rapid halo CME on May 17, 2012, at 01:48 UT. Figure 1(A) shows the GLE event on May 17, 2012 associated with CME and solar flare event. Interplanetary magnetic field is also showing some change on their amplitude in comparison to the other non GLE days. Figure 1(A) 1(B) & 1(C) shows the GLE event on May17, 2012 associated with CME and solar flare event.

GLE 72 was recorded by Oulu NM on September 10, 2017 and by using that data we found 4.95% of increase in CRI. On September 10, we found strong X-class (X8.2) flare at NOAA active region S08W88 with onset time 15:35 UT and peak at 16:06 UT before the time of GLE no flare events recorded as strong as X8.2. At 16:00 UT a strong CME event happened i.e.

Ejection of tremendous amount of plasma release with speed of 3163 m/s which effects the count rate at earth surface. A SEP event also happened on 16:25 UT at 1490 pfu of solar flux which is strongly associated with GLE and 40 sunspots were found during the day of this GLE. Figure 2(A) 2(B) & 2(C) shows the GLE event on September 10, 2017 began at 15:00 UT an associated with CME and solar flare event and reached its peak at 18:00 UT on same day. This was the last GLE event of solar cycle 24

GLE73 GLE amplitude was ~ 2.2% recorded by Oulu neutron monitor station October 27-28, 2021. We have studied solar flare and CME events, as well as a few days prior to the GLE onset day, in an effort to identify the solar sources causing the event. There was a brief period of initial phase increasing solar activity at the end of October 2021 during the ascending phase of solar cycle 25. On October 26, 2021, we found total 14 flares, of which 12 were C-class and 2 were M-class. On October 27, we found a total of 19 flares, of which 18 were C-class and 1 was B-class. We found total of 12 flares on October 28, 2021, of which 9 are C-class, 2 are M-class, and 1 is the strongest X-class flare produced by active NOAA region 12887. This was the first GLE (~2.2%) event of initial phase of 25th solar cycle. The GLE began on October 28, 2021 at 15:15 UT and peaked on October 28, 2021 at 17:00 UT. When it came to the solar proton event, it took place on October 28, 2021 starting around 16:35 UT and peaked on October 29, 2021 at 02:50 UT. The proton fluxes about 29 for energies > 10 MeV was recorded with type II and IV radio emission.

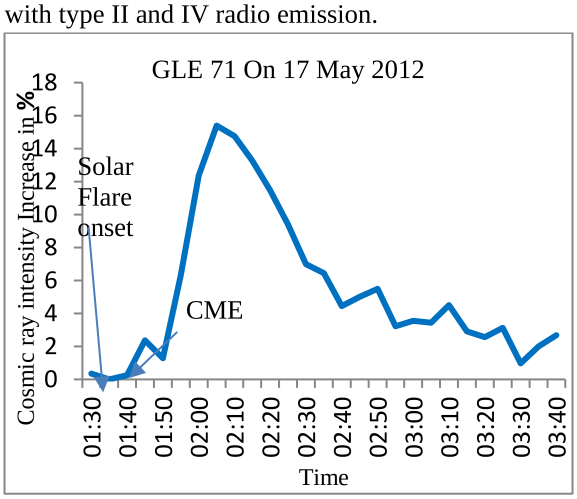

Figure 1(A) the GLE event on 17 May, 2012 associated with CME and solar flare event

The X-ray flare of class X1.0 with importance 2N, location S26W04 produced by active region 12887, associated with GLE event was began on 28 October 2021 at 15:17 UT and peaked on 28 October 2021 at 15:35 UT. Associated the flare a CME was with high-speed of 1519 km/s, SSN equals 100. The abrupt increase in cosmic ray intensity was a hallmark of the rapid halo CME on October 28, 2021, at 15:48 UT. Figure 3(A) shows the GLE event happening on October28, 2021 associated with CME and solar flare event.

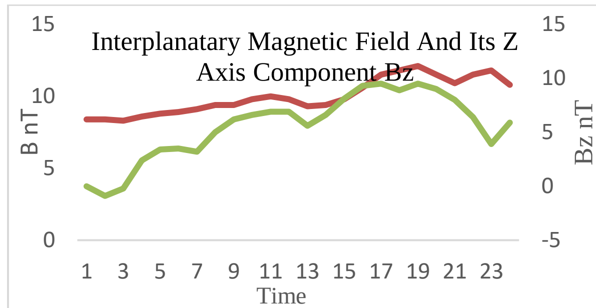

Figure 1(B) Shows the variation of Interplanetary Magnetic Field on the day of GLE 71

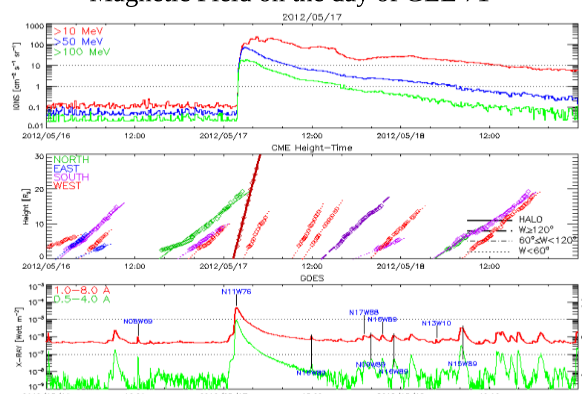

Figure 1(C) Shows the variation of SEP events on the day of GLE 71

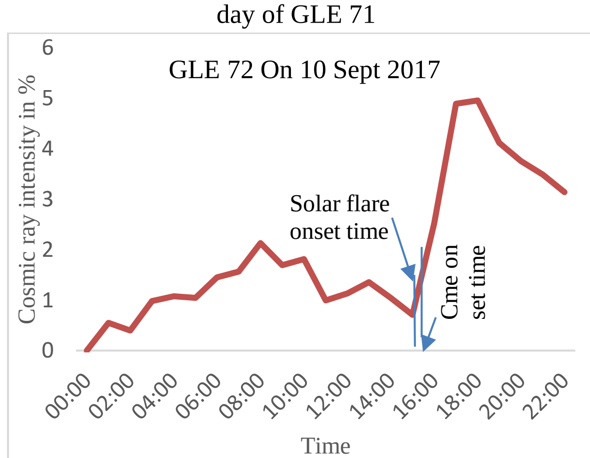

Figure 2(A) Shows the Onset Time of Solar Flare and CME on the day of GLE 72

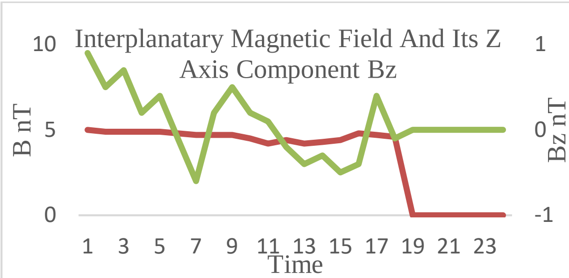

Figure 2(B) Shows the variation of Interplanetary Magnetic Field on the day of GLE 72

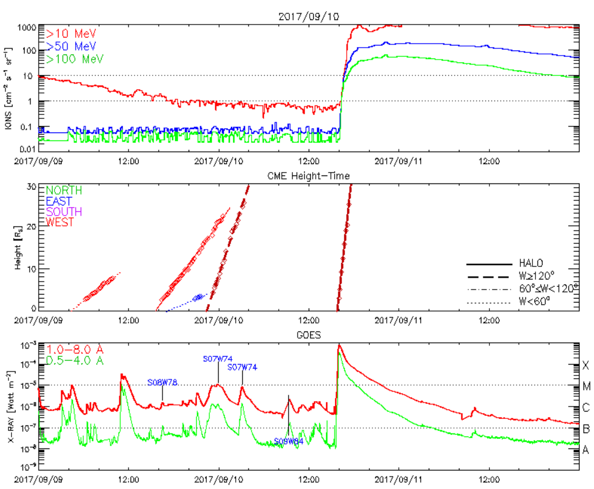

Figure 2(C) Shows the variation of SEP events on the day of GLE 72

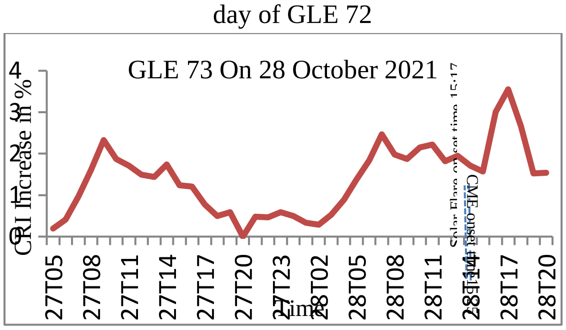

Figure 3(A) Shows the onset time of solar flare and CME on the day of GLE 73

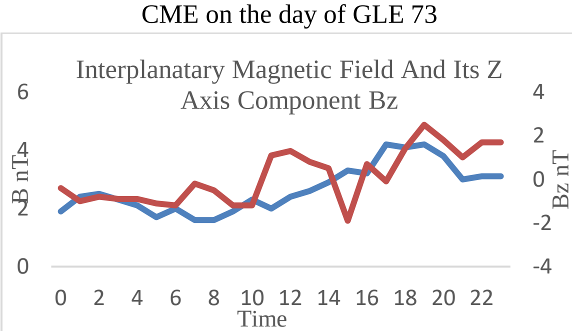

Figure 3(B) Shows the variation of Interplanetary Magnetic Field on the day of GLE 73

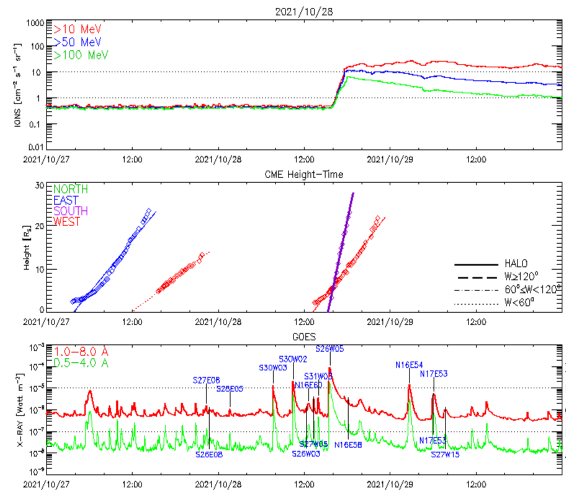

Figure 3(C) Shows the variation of SEP events on the day of GLE 73

IV. CONCLUSION

Harder energetic particle fluxes having strong fluences are presumably necessary for prompting GLEs. Since a solar flare is a violent explosion of solar energetic particles, it may also sometimes cause GLE. The solar flare characterized by direct proportionality with GLE peak seems to be amenable. Alternatively, a connection between CME-driven interplanetary shock and flare may produce GLE. CME alone presumably does not cause GLE. The variation of the GLEs may depend on the magnitude of the intensity of the flare, solar energetic particle, and CME-driven. A further study, an extended investigation into GLE-associated solar, interplanetary, and geophysical para-meters, and longitudinal variations of GLEs will be con-ducted based on high-resolution data of cosmic ray intensity from different neutron monitor stations and space satellites.

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