Investigation of the Cosmic Rays Associated with Ground Level Enhancement Events during Solar Cycle 24

Sura I. Gburi and Najat M. R. AL-Ubaidi
Astronomy and Space, college of Science, University of Baghdad
najatmr10@yahoo.com

Abstract

In the Sun, particles mostly protons (positively charged) with energies up to several hundred (MeV) are escaped during periods of intense flare activity. These particles are solar cosmic radiation, which are very small particles move at nearly the speed of light through space. The flare and coronal mass ejection (CME) may also cause a sharp rise in the cosmic ray intensity (CRI) at the Earth atmosphere. There are indications that the most energetic events occurred in the minimum phase of solar activity. When cosmic rays enter the Earth's atmosphere they collide with atoms and molecules, as the Sun's magnetic field became weak the cosmic rays are flooding into the solar system from deep space, causing health risks to space travelers. Sudden increases in the cosmic ray intensity called Ground level enhancements (GLEs) are measured or recorded on Earth's sea level by neutron monitor (NM). The main objective of this research is to find the relation between cosmic ray and the GLE events and other solar activity parameters during the period years (2008-2019) for solar cycle (24). In this work satellite data of GLE based on ground level station Oulu NM (ONM) are taken situated in north Finland at the height of 15m above sea level in the geographic coordinates (65.05°N; 25.47°E). The observational spectrum of two GLEs occurred during solar cycle 24 are investigated, one in 17 May 2012 which known as GLE71 and the other in 10 September 2017 as GLE72, in which the solar energetic particle was the larger in this solar cycle. Data of these two events indicate that the presence of different between them are due to populations of different energy spectrum, period of time occurrence, and increasing rate of (CRI).

Keywords: Cosmic ray; CME; GLE; Solar cycle 24.

1- Introduction

From the Sun, during the period of high solar activity (solar disturbance time) or when there are intense flare activity the positively charged particles protons with high energies reach to several hundred (MeV) are ejected, these particles are termed solar cosmic rays (SCR). There is, in addition to this solar source a galactic cosmic radiation (GCR), which
is plainly not of solar origin and a steady background of high-energy radiation. The cosmic rays consist of electrons, neutrons and atomic nuclei, which have been accelerated to very high speed [1]. The astrophysical origin of cosmic rays is from, primary particles such as electrons, protons and helium. The cosmic ray's elemental composition provides information on chemical fractionation in the source region as well as some insight into the nature of this region and of the propagation of cosmic rays in interstellar space, the variation of the charge and mass composition with energy, their energy spectra can be related to the acceleration process and to particle transport in the galaxy [2].

Several attempts and Studies were conducted by scientists to improve data taking from neutron monitor (NM) for ground stations and for several and different regions, Bütikofer and Flückiger in 1999 propose a technique which compensates for this effect and improves the reliability of pressure corrected NM data [3]. Mishev et al (2013) provide a new study of variation cosmic ray sea-level (NM) on different temporal and spatial scales by adding theoretical yield function that is investigated with experimental data [4]. Mishev et al in (2019) found a great significant correlation between neutron monitor peak count rate and the maximum effective dose rate increase during GLEs is observed propose to use the maximal count rate increase as a proxy for assessment of the effective dose at flight altitude during strong solar particle events [5]. Mishev et al. (2020) provide a new yield function of the standard sea-level NM, isotropic flux of cosmic ray (CR) particles, and extended here to different altitudes of the atmospheric depths from sea level up to 500 g/cm2 [6]. Mishev and Usoskin in 2019 and 2020 used data from NM to analysis ground level enhancement (GLE) event for space weather applications. Their study revealed that the effect of space weather change is related to global NM network which is a useful tool for estimation namely the exposure of aircrew due to galactic and solar cosmic ray origin. The derived spectra and angular distributions will be integrated into the GLE database [7, 8].

Many researchers studied the relationship between cosmic rays and solar activity through the parameters GLE, coronal mass ejection (CME), and others Firoz et al. 2010 et al. [9]; Firoz 2011 et al. [10]; Firoz et al. 2014 [11], Firoz et al. 2019b [12] and Firoz et al. 2019 [13] their study show that the production of a GLE need harder energetic particle fluxes having strong cast above the background emission due to galactic cosmic rays (GCR). Statistical analysis has shown that a conjunction between CME driven interplanetary shock and flare are likely to be the cause of GLEs, but CMEs alone probably does not cause GLEs. The variation of the GLEs may depend on the magnitude of the solar energetic particle, intensity of the flare and CME pushed out. Yu Balabin in 2013 presents the analysis of solar cycle 24, which started at 2009 and the GLE71 on May 17, 2012 has become the first event of this cycle [14]. Le and Liu 2020, their studies covered the solar cycle distribution of GLEs for the period from 1942–2017 and source location. The GLEs which are occurred during this period distributed in the longitudinal area taken from 30°E to 150°W. Statistical results show that 44.3% of GLE revealed in the
ascending period and 55.7% of the GLE appeared in the descending phases of the solar cycles, while 83% of them appeared two years before solar cycle peak and the three years after solar cycle peak. They found that there are a poor correlation between the numbers of GLEs and the amplitude of the solar cycle [15].

The solar energetic particles (SEPs) are the dominant source of ionization in Earth’s upper atmosphere and a major source of natural radiation on the Earth’s surface. The magnitude of the SEP flux intensity increase specifies the enhancement of the radiation level, which can cause damage to satellite electronics and also pose a radiation hazard to astronauts and air crews [13]. When relativistic solar protons (RSPs) reach the Earth surface, the interaction between (RSPs) and Earth’s atmosphere will lead to enhance the cosmic ray intensity which is referred to ground level events (GLEs) [15]. GLE appears in the cosmic-ray temporal profile conspicuously as a sudden, sharp, and short lived [12]. For each solar cycle a few times detection of SCR particles by ground-based detectors on average are occurs. Each GLE has its own typical spectrum, amplitude, duration, and spatial distribution of flux. The worldwide network of neutron monitors (NMs) using the geomagnetic field as a giant magnetic spectrometer enables to determinate the characteristics of the SCRs near Earth during a GLE in the energy range ~500 MeV to ~15 GeV [16]. While the energetic particle fluxes comprise softer and harder spectra, the softer phase representing in MeV energetic particle fluxes refers to the solar energetic particle (SEP) event, and the harder phase representing in GeV energetic particle fluxes refers to the GLE event [17]. GLE events are subset of large SEP events (~15% of events identified by Space Weather Prediction Center with particularly hard spectra, making them a substantial space weather hazard to space-based instrumentation and exposed astronauts. Large solar flare is associated with a GLEs, the flare may not be related to the production of the protons high energy which produce the GLE that affects the Earth atmosphere. The cosmic ray intensity intensify to a sharp increase due to the propagation process of the accelerated higher energy particles, then the sharp rise of cosmic ray intensity returns to the background level when the acceleration of particles ends, this process measured at the ground by neutron monitors takes tens of minutes to hours. Flare and CME also cause a sharp rise in the cosmic ray intensity at the Earth's atmosphere [18]. This is particularly the case for the current solar cycle (cycle 24) in which only two GLE events have been identified. Several aspects of cycle 24 have been shown to be significantly weaker than those of cycle 23, including the solar wind speed and the magnetic field strength [19]. The number of large SEP events is no exception [20 and 21]. Also there are many studies about the solar cycle 24 which includes various topics in different aspects of solar activities [22, 23, 24, 25, 26, and 27]. The aim of this research we try to find the correlation between cosmic ray and the GLE events and other solar activity parameters during the period years (2008-2019) for solar cycle (24), in this solar
cycle only two events occurred one on 17 May 2012 and the other on 10 September 2017, which are taken as a study case for duration time of CME.

2. Data Selection and Analyses

2.1 Solar Cycle Distribution of the GLEs

The solar cycle activity almost spends 11-years is a main dominant characteristic of the Sun [28]. According to the solar activity through the smoothed monthly mean sunspot numbers (SMMSNs) are usually used to describe solar cycle, daily total sunspot number and the GLE events that occurred during years 2008–2019, in figure (1) the GLE events is shown during solar cycle distribution. At the first month the minimum of a solar cycle started then SMMSNs increases gradually and reach the peak of cycle, the maximum is defined as the ascending phase take the period from the first month to the month when SMMSNs have reached its peak of the solar cycle. The period from the one month after the month when SMMSNs reach its peak to the last month of the minimum solar cycle is defined as the descending phase of the solar cycle. Sunspot numbers (SSN) for the cycle 24 that takes a long duration and minimum in activity levels [28]. The data obtain from Sunspot Index and Long-term Solar Observations (http://sidc.oma.be/silso/datafiles.).

![Solar cycle 24](image)

Figure 1. Smoothed monthly mean sunspot numbers (SMMSNs) red line, daily total sunspot number blue line and the GLE events black arrow that occurred during years 2008–2019 in solar cycle 24.
2.2. Cosmic Ray Intensity

According to several works done by Shea et al. (1985) [29] and Poluianov et al. (2017) [30], a standardized format for determining cosmic ray ground level event data are given. On this basis only one NM station "Oulu Neutron Monitor (ONM)" has clearly measured and recorded these GLE events. Assuming that the spectrum derived using this high altitude neutron monitor’s is given a proper description of the energetic flux that reaches the Earth sea level. We analyzed the data of cosmic ray intensity (CRI) registered by ONM (see http://cosmicrays.oulu.fi/) for the period of December 2008 through December 2019 (solar cycle 24). The station (ONM) is situated in north Finland at the height of (15m) above Earth's sea level in the geographic coordinates of (65.05°N) latitude and (25.47°E) longitude, the local vertical geomagnetic cut off rigidity is almost (0.8 GV). It is a standard consisting of three units with each of three counters (uncorrected counter rate (in counts/ min), barometric pressure (in mb) and corrected count rate (in counts/min) [31]. For this study the solar cycle 24 data of CRI from the ONM stations preferred, because its data has high resolution for a long time period and correct reliable. The characteristics of these two events described in figure (2) below.

The lists of GLEs given in the catalog of the ONM have been considered as references. 5 min data of CRI are analyzed according to their occurrence time of GLEs, as data available for 5 min pressure corrected, for this study the increase rates (%) of two GLE events are deduced one on 17 May 2012 and the other on 10 September 2017. High energy solar protons during this event were recorded by ground based NM Oulu station.
Figure 2. Using 5-minute resolution data of cosmic ray intensity (CRI) for 2008–2019, hourly averaged CRI is exhibited. The sudden, sharp and short-lived increase in cosmic ray intensity is known as ground level enhancement (GLE). The selected GLEs studied are mentioned in this figure. It is clearly seen in the figure that occurrences of GLEs are independent of the maximum and minimum of the cosmic ray cycles.

2.2.1. GLE of May 17, 2012

This event was quite small, highly an isotropic and was only observed at high latitudes and at a few stations at lower latitudes with a geomagnetic cutoff <3 GV. There is a debate about which stations have registered the GLE of May 17, 2012, and given the smallness of the event at Ground level.

This event took place due to a medium intensity solar flare (M5.1, N12W83) and shock CME with high-speed (1582 km/s) [27], as shown in figure (3). Many researchers were involved in the study of the different characteristics of this event and its origin solar flare (e.g. Li et al., 2013 [22]; Papaioannou et al., 2014 [23]; Gopalswamy et al., 2014 [20]; Augusto et al., 2018 [18]). The data in figure (3) are taken from NOAA, for a period in which the event occurred from 15 to 19 May 2012, correspond to 5 minute average integral proton flux measured by a Geostationary Operational Environmental Satellite
(GOES) for each of energy thresholds greater than (1, 5, 10, 30, 50, and 100 MeV), vertical arrows indicate solar event with flare type M5.1.

![GLE 71](image)

Figure 3. Five minute averaged integral proton fluxes (in pfu = protons/ cm$^2$·s·sr) as measured by a GOES satellite for each of the energy thresholds >1, >5, >10, >50, and >100 MeV, from 15 -19 May 2012. Vertical arrows indicate analyzed of solar event with M5.1 flare.

In comparison with other SEP events identified as being of space weather interest, GLE events typically have significantly harder spectra with an average power law index of 3.18 at energies >40 MeV (Mewaldt et al., 2012). The combined hard spectra and large intensity >50MeV/nucleons makes GLE events a particular danger to space based instrumentation and exposed astronauts [24]. The method for deducing the increase rate of GLE that used is given by considering the pre increase of the CRI for GLE as the background count rate preceding the time CRI starts increasing toward a sharp rise. To measure the increase in sharp rise, considered the background as the average of the pre increase. The difference between each 5 min CRI and the average of the pre increase is the increase above the background level. The increase rate (%) of the CRI for GLE is computed by equation (1) [9]
\[ I_r(\%) = \left( \frac{\sum_{j=1}^{m} I_j}{\sum_{k=1}^{m} I_k} - 1 \right) \times 100 \]  \hspace{1cm} \text{(1)}

Where \( I_r(\%) \) is the increase rate, \( I_j \) is the CRI of the time series for the whole time window of the GLE event. \( j \) is defined as \((j = 1, 2, 3 \ldots n)\) for the whole time window is taken as 24 hours of GLE event that counted data number as \((n = 24 \times 12 = 288)\) for (5-minute) resolution. \( I_k \) is the pre increase i.e. \( I_k \) is the CRI before the onset of the rise of CRI towards GLE peak and \( m \) is the number of data of the pre increase CRI. The series of the data of pre increase CRI is defined as \((k = 1, 2, 3 \ldots m)\).

This deduction process also satisfies the criteria mentioned in the catalog of the ONM for modeling the global GLE behavior. According to our present understandings, GLE and GLE event are something different see figure (4). GLE implies the sudden, sharp and short lived part of CRI and GLE event indicates the CRI of the whole time window (GLE peak plus background before and after the peak). The focus of our study is to look into the relationships of GLEs as well as GLE-events with simultaneous solar factors.

Figure. 4: show how the increase rate (\%) of GLE has been deduced is shown. 5-minute resolution data of CRI at ONM for GLE71 is at the top panel and its corrected count rate

![Figure 4](image-url)
(cts/min) and increase rate Ir (%) is at the bottom panel. The peak time (Tpeak) of the GLE is when the increase rate Ir (%) is the highest. The start time (Tstart) is when the Ir (%) starts increasing above zero level, and the end time (Tend) is when it minimizes again to zero level. The pre-increase CRI represents the CRI before the onset of the sudden rise in CRI. \( m \) is the number of data of the pre-increase CRI. The whole window of GLE event is taken as 24 hours that counted data number as \( n = 24 \times 12 = 288 \) for 5-minute resolution.

![Graphs showing ground level enhancement](image)

Figure. 5: ground level enhancement 71 (a) increasing (b) uncorrect pressure (c) corrected pressure (d) pressure for event GL71.

This presented 5- min NM data for atmospheric pressure, there are three types of neutron monitor data which are corrected for atmospheric pressure, atmospheric pressure and neutron monitor data uncorrected for atmospheric. The barometric pressure coefficient for NM depends on the characteristics of the detector, on the altitude and the geomagnetic of it location as well as on the primary cosmic ray spectrum. It has a value of approximately (1%/mmHg). The plot shows OULU NM pressure corrected count rate for the required period scaled (17 may 2012). The plot scaled as present 100% where 100% is the average cosmic intensity level for the interval. Figure (5) above show uncorrected count rate (in counts/min), corrected count rate (in counts/min), barometric pressure (in mb) from OULU NM station for 5-min resolution in GLE 71.
2.2.2. GLE of September 10, 2017

At the beginning of September 2017 there was a period of solar activity established at the minimum of the solar cycle 24, in the active region AR2673 which produced flares four powerful are X class and 27 M class, including the strongest flare (X9.3, S08W83) on September 6, 2017 of this cycle. This was the one that produced intensive solar terrestrial disturbances including a severe geomagnetic storm on September 7 and 8. Solar activity decreased on 9 and 10 September but on 10 September, a X8.2 class solar flare induced solar energetic particles with high energies which is the second strongest flare in solar cycle 24. This flare led to the second GLE of the solar cycle 24, identified as GLE72, on September 10, 2017 as shown in figure (6). There are some studies involved on properties of this event and the origin of solar flare [18] [24-26].

Figure. 6. Five minute averaged integral proton fluxes (in pfu = protons/ cm²·s·sr) as measured by a GOES satellite for each of the energy thresholds: >10, >50, and >100 MeV, from 04 to 15 September 2017. Vertical arrows indicate three analyzed solar events with M5.5, X9.3, and X8.2 flares.

As in figure (3) the data are issued from NOAA; the correspond to 5 minute average integral proton flux measured from 4 - 15 September 2017 by a GOES satellite for each of energy thresholds: > 10 > 50 , and >100 MeV, from 4 to 15 September 2017, vertical arrows indicate three analyzed solar events with M5.5,X9.3 and X8.2 flare. Figure (7) shows the increasing rate (%) for GLE72.
Figure 7. Shows how the increase rate (%) of GLE has been deduced is shown. 5-minute resolution data of CRI at ONM for GLE72 is at the top panel and its corrected count rate (cts/min) and increase rate, $I_r$ (%) is at the bottom panel. The peak time ($T_{peak}$) of the GLE is when the increase rate $I_r$ (%) is the highest. The start time ($T_{start}$) is when the $I_r$ (%) starts increasing above zero level, and the end time ($T_{end}$) is when it minimizes again to zero level. The pre-increase CRI represents the CRI before the onset of the sudden rise in CRI. $m$ is the number of data of the pre-increase CRI. The whole window of GLE event is taken as 24 hours that counted data number as $(n = 24 \times 12 = 288)$ for (5-minute resolution).
The results of GLE analysis using the data of the worldwide NM network are highly dependent on the accuracy of the used NM response that accounts for the shower of secondary cosmic ray particles in the Earth’s atmosphere and the detection of the secondary nucleons by a NM. The discrepancy between different yield functions is in particular present in the energy range where NMs are most sensitive to SCR. The number of GLEs that occurred during a solar cycle has a poor correlation with the amplitude of the associated solar cycle. A solar particle Event (SEP) took place on May 17th 2012, starting around 1:45UTC with maximum intensity at around 02:05 UT this event was sufficiently energetic to be detected by ground level neutron monitors (GLNM) and will be registered as a Ground level Enhancement (GLE71). Recent studies on the first GLE
event (GLE71 2012 May 17) of solar cycle 24 proposed that CME driven shock played a leading role in causing the event.

In the polar regions, where the Earth is less shielded by its magnetic field, the GLNM count rate increased relative to the count rate on 17 of May (average from 1:45 to 3:30) for a short time of occurrence spends 2 hour and 54 minute with peak intensity reach (15%) respective to background galactic cosmic ray, in the northern hemisphere, locally (NM OULU, 5 min average).

A Ground level Enhancement (GLE72) Event took place on 10 September 2017, starting about 16:20UT with the peak intensity on 11 September 2017 at around 00:55 UT. The increasing rate in CRI is (8%) and its period of time almost (1 day and 40 min) which is longest than the event of GLE 71 but lower increasing quantity. The increased count rates fell clearly with decreasing magnetic latitude and so one can expect that only high latitudes (> 60°) were affected. Table (1) is a summary of the properties for each GLE 71 and GLE72 in solar cycle 24

Table 1. Summary of the properties for each GLE 71 and GLE72

| No. | T_start   | T_peak       | Increase rate | Period of event | Source |
|-----|-----------|--------------|---------------|-----------------|--------|
|     |           |              | Ir            |                 |        |
| GLE 71 | 17/5/2012 | 17/5/2012   | 15%           | 2 hour:40 min   | M5.1   |
|      | 1:45      | 2:05         |               |                 |        |
| GLE 72 | 10/9/2017 | 11/9/2017    | 8%            | 1 day 40 min    | X8.2   |

3.1. Effect of GLE

The hourly average data used are provided by the international space related research centers that is operating mission as nodes on the internet (OMNI) sited (http://omniweb.gsfc.nasa.gov/ow.html). The OMNI system has been conducting its research using many ground and space based GPS and satellite stations since long ago. Investigating the effect of two GLE events has different increase rate and duration on the variation of solar wind parameters; velocity of solar wind (Vsw in km/sec), solar wind density (Dsw in N/cm^3, where N is the number of particles), Bz component of the Interplanetary Magnetic Field (IMF) measured in (nT) also geomagnetic indices: planetary Kp-index and Disturbance storm time index Dst in (nT). This study during intense cosmic ray has two ground level enhancements (GLE 71 and GLE 72) which is very important because it gives us the response time of the phenomenon and can give us an idea of the mechanism operating in the energy transfer. Using equation (1) time of these events can be determined to check the changes in these parameters.
a. GLE of May 17, 2012

In this paper we investigate the effect of GLE event which calculate in equation 1 on Southward component Bz along with solar wind velocity on cosmic ray intensity (CRI) during following time intervals when the GLE amplitude was >= 5% recorded by OULU neutron monitor station: 16-17 may 2012, 10-11September 2017. We have searched for the solar sources responsible for above events by tracking back the smoothed monthly mean sunspot numbers (SMMSNs), daily total sunspot number, also determine solar flare associated CME, and, some days before the onset of GLE.

This was the first GLE (~15%) event of maximum phase of 24th solar cycle. It originated location (N12 W83) which unleashed X-ray flare of class M5.1 on 17 May 2012 at 1:45 UT. Associated the flare a CME was with high speed of 1582 km/sec, SSN equals 116. On 17 May 2012, the fast CME shock waves featured by sudden jump in cosmic ray intensity (CRI), and almost all parameter that chosen gradually increased Bz solar wind proton density, Dst except Kp index which is gradually increased. Otherwise the increase is not significantly changing in solar wind proton speed as shown in Figure (9) below.
Figure 9. (from top to bottom) CRI, southward component $B_z$, solar wind density, solar wind speed, $K_p$ and $Dst$ indices, (all hourly averaged)plots from 16 to 17 May 2012. Vertical line marks the duration of GLE event.
From figure (9), it is noticed that SW velocity groundling decline from 378 Km/sec at start the event to 357 Km/sec at the end of event, Bz value fallen to -2.9 nT at the peak of event, the value of Kp had fast regression. Thus due to interplanetary Coronal mass ejections (ICME) impacting on slow solar wind there was a sheath upstream of ICME led by a fast forward shock causing GLE. On other hand Solar wind proton density groundling increase to 5.5 and continue increasing after the end of event because the ionization that resulting from increase number of particles entering the Earth's ionosphere during the GLE and reconnection need time to remove the effect.

b. GLE of September 10, 2017

GLE 72 was observed in the declining phase of 24\textsuperscript{th} solar cycle. An energetic solar phenomenon was observed in the active region AR2673 (S08W83) on 10 September 2017. The SSN was 34. It sparked a solar flare, X8.2 at 16:20UT. An intensive GLE with magnitude 8\% was recorded by OULU neutron monitors. It is evident from the figure (10) was marked by an extraordinary large increase in Kp and Dst indices. The solar wind velocity, density and BzThe relationship is unclear because of the loss of information from the OMNI website.
4. Conclusion

In the present analysis we examined two Ground level enchainment events in the period (2008-2019) in association with solar interplanetary and geomagnetic parameters to find...
the causes of large increase in cosmic ray neutron monitor counts at the Earth. It is observed that the initiation of GLE is linked to the appearance of active regions on solar disk which is erupted fast CMEs associated by strong flares. The effects of GLE event preceded by large CRI variations, sudden rise in solar wind density and Bz, increase in cosmic ray flux and decrease in geomagnetic activity the Dst and decrease in geomagnetic activity the kp. This paper summarizes the extreme solar activity and its implications via GLE events during the maximum and declining phase of the solar cycle 24: 17 May 2012 and 10 September 2017.

We have compiled and compared the properties of GLE which has the potential of yielding a lot of information for space weather applications. The solar cycle effect is not very significant in case of very large GLE events. It is seen that high duration of increasing in intensity of GLE have occurred in the descending phase of solar cycle. We can say that large GLE event increasing (~15%) is most common near solar maximum but occur around sunspot maximum (116) throughout the cycle. Solar cycle 24 is poor of number of GLE, The flare associated with shockwave in GLE 71 increase cosmic ray intensity. The origin of GLE 72 is from second strongest solar flare in cycle 24. The different in source origin cause different in GLE spectrum and other properties.

Acknowledgements

Many thanks for Solar Influences Data Analysis Center (SIDC) for providing the smooth monthly mean sunspot numbers (SMMSNs) [http://sidc.oma.be/silso/datafiles] and the Oulu neutron monitor (ONM) for providing data for cosmic rays [http://cosmicrays.oulu.fi/]. This research was done at the University of Baghdad/ College of Science/ Department of Astronomy and Space, my thanks and appreciation.

Reference

1. Hansjörg Schlaepfer, (2003); "Cosmic Rays", International Space Science Institute, SPATIUM Published by the Association Pro ISISI.
2. Frank B. Mc.Donald and Vladimir S. Ptuskin, 2001; Galactic Cosmic Rays, The Century of Space Science, Kluwer Academic Publishers; pp. 677–697.
3. Bütikofer R., and Flückiger E. O., (1999) "Pressure Correction of GLE Measurements in Turbulent Winds", 26th International Cosmic Ray Conference (ICRC26), August 17-25, p. 395, Salt Lake City, Utah.
4. Mishev A. L., Usoskin I. G., and Kovaltsov G. A., 2013 "Neutron monitor yield function: New improved computations", Journal of Geophysical Research: Space Physics, Vol. 118, pp. 2783–2788. doi:10.1002/jgra.50325, 2013.
5. Mishev A., Usoskin I., Tuohino S. and Ibragimov A., (2019) "The upgraded GLE database includes assessment of radiation exposure at flight altitudes", 26th Extended European Cosmic Ray Symposium, IOP Conf. Series: Journal of Physics: Conf. Series 1181 (2019)12061. Doi:10.1088/1742-6596/1181/1/012061.
6. Mishev A. L., Sergey A. Koldobskiy, Gennady A. Kovaltsov, Agnieszka G., and Ilya G. Usoskin. (2020) "Updated Neutron-Monitor Yield Function: Bridging Between In Situ and Ground-Based Cosmic Ray Measurements", JGR Space Physics, Research Article.
7. Mishev A., and Usoskin I., (2019) "Analysis of sub-GLE and GLE events using NM data: space weather applications", 26th Extended European Cosmic Ray Symposium, IOP Conf. Series: Journal of Physics: Conf. Series 1181 (2019)12006. Doi: 10.1088/1742-6596/1181/1/012006.

8. Mishev A. L. and Usoskin I. G., (2020) "Current status and possible extension of the global neutron monitor network", arXiv: 2005.12621v1 [physics.space-ph] 26 May 2020.

9. Firoz K. A., Cho K. S., Hwang J., Phani Kumar D. V., Lee J. J., Oh S. Y., Kaushik S. C., Kudela K., Rybanský M. and Dorman L. I., (2010), "Characteristics of ground-level enhancement associated solar flares, coronal mass ejections, and solar energetic particles", Journal Geophysics Research, 331, pp. 469–484. Doi: 10.1007/s10509-010-0473-0.

10. Firoz K. A., Zhang Q. M., Gan W. Q., Li Y. P., Rodríguez-Pacheco J., Moon Y.-J., Kudela K., Park Y.-D., and Dorman L. I. (2014) "An interpretation of GLE71 concurrent CME driven shockwave", The Astrophysical Journal Supplement Series, 213:24 (14pp). Doi:10.1088/0067-0049/213/2/24.

11. Firoz K. A., Gan W. Q., Li Y. P., Rodríguez-Pacheco J., and Kudela K., (2019) "On the Possible Mechanism of GLE Initiation" The Astrophysical Journal, 872, 178, 13pp, February 20. https://doi.org/10.3847/1538-4357/ab0381

12. Firoz K. A., Gan W. Q., Moon Y. J., Rodriguez-Pacheco J., and Li Y. P., (2019b) "On the Relation between Flare and CME during GLE-SEP and Non-GLE-SEP Events", The Astrophysical Journal, 883(91). Doi: 10.3847/1538-4357/ab3c4e.

13. Yu. V. Balabin, Germanenko A. V., Vashenyuk E. V., and Gvozdevsky B. B., (2013) "The first GLE of the new 24th solar cycle", In: Proceedings 33rd International Cosmic Ray Conference (ICRC), Rio de Janeiro, Brazil, Polar Geophysical institute, Apatity, Russia, “Physics of Auroral Phenomena”, Proc. XXXVI Annual Seminar, Apatity, pp. 103 - 105.

14. Le G., and Liu G., (2020) "The Properties of Source Locations and Solar Cycle Distribution of GLEs during 1942–2017", Sol Phys 295, 35, https://doi.org/10.1007/s11207-020-01600-8.

15. Büttikofer R., Lückiger E., Alabin Y., and Belov N., (2013) "The reliability of GLE analysis based on neutron monitor data – a critical review", In Proc. of 33rd international cosmic ray conference, Rio de Janeiro, Brazil, 2-9 July, 863.

16. Augusto C. R. A., Navia C. E., de Oliveira M. N., Nepomuceno A. A., Fauth A. C., Kopenkin V., and Sinzi T., (2018) "Relativistic proton levels from region AR2673 (GLE #72) and the heliospheric current sheet as a Sun-Earth magnetic connection", Publications of the Astronomical Society of the Pacific, 131:024401 (14pp). https://doi.org/10.1088/1538-3873/aaeb7f

17. Augusto C. R. A., Kopenkin V., Navia C. E., Felicio A. C. S., Freire F., Pinto A. C. S., et al., (2018) "Was the GLE on May 17, 2012 linked with the M5.1-class flare the first in the 24th solar cycle?", Astroph. SR, (9pp).

19. McComas D. J., Angold N., Elliott H. A., Livadiotis G., Schwadron N. A., Skoug R. M., and Smith C. W., (2013) "Weakest solar wind of the space age and the current “mini” solar maximum", Astrophysical Journal, 779:2 (10pp). Doi:10.1088/0004-637X/779/1/2

20. Gopalswamy N., Xie H., Akiyama S., Mäkelä P. A., and Yashiro S., (2014) "Major solar eruptions and high-energy particle events during solar cycle 24", Earth, Planets and Space, 66:104, (15pp). http://www.earth-planets-space.com/content/66/1/104

21. Mewaldt R. A., Li G., Hu J., and Cohen C. M. S., (2017) "What is causing the deficit of high-energy solar particles in solar cycle 24?", Proceedings of 35th International Cosmic Ray Conference (ICRC2017), Bexco, Busan, Korea, 12-20 July, 2017, 111, (8pp).
22. Li C., Firoz K. A., Sun L. P., and Miroshnichenko L. I., (2013) "Electron and proton acceleration during the first ground level enhancement event of solar cycle 24", The Astrophysical Journal, 770, 34, (11pp). Doi:10.1088/0004-637X/770/1/34
23. Papaioannou A., Souvatzoglou G., Paschalis P., Gerontidou M., and Mavromichalaki H., (2014) "The first ground-level enhancement of solar cycle 24 on 17 May 2012 and its real-time detection", Sol. Phys. 289, pp. 423–436.
24. Cohen C. M. S., and Mewaldt R. A., (2018) "The ground-level enhancement event of September 2017 and other large solar energetic particle events of cycle 24", Space Weather, 16, pp.1616–1623. Doi: 10.1029/2018SW002006
25. Gopalswamy N., Yashiro S., Mekel1 P., Xie H., Akiyama S., and Monstein C., (2018) "Extreme kinematics of the 2017 September 10 solar eruption and the spectral characteristics of the associated energetic particles", Astrophysical Journal Letter, 863, (13pp). Doi: 10.3847/2041-8213/aad86c
26. Zhao M.-X., Le G.-M., and Chi Y.-T., (2018) "Investigation of the possible source for solar energetic particle event of 2017 September 10, arXiv: 1805.01082v1 [astro-ph.SR] 3 May, (13pp). Doi: 10.1088/1674-4527/18/7/74
27. Jorge A. Perez-Peraza, Juan C. Ma´rquez-Adame, Jogelio A. Caballero-Lopez, Roberto R., and Manzano Islas, (2020) "Spectra of the two official GLEs of solar cycle 24", Advances in Space Research, 65, pp. 663–676. https://doi.org/10.1016/j.asr.2019.10.021
28. Balogh A., Hudson H. S., Petrovay K., and Steiger R., (2014) "Introduction to the Solar Activity Cycle: Overview of Causes and Consequences", Space Science Reviews, 186, (15pp). doi: 10.1007/s11214-014-0125-8
29. Ewaid, S.H., Abed, S.A., 2017. Water quality index for Al-Gharraf river, southern Iraq. Egypt. J. Aquatic Res. 43 (2), 117–122. http://dx.doi.org/10.1016/j.ejar.201703001.
30. Ewaid, S.H.; Abed, S.A.; Al-Ansari, N. Crop Water Requirements and Irrigation Schedules for Some Major Crops in Southern Iraq. Water 2019, 11, 756.
31. Ewaid, S.H.; Abed, S.A.; Al-Ansari, N. Water Footprint of Wheat in Iraq. Water 2019, 11, 535.
32. Salwan Ali Abed et al 2019 J. Phys.: Conf. Ser. 1294 072025.
33. Ewaid, S.H.; Abed, S.A.; Al-Ansari, N. Assessment of Main Cereal Crop Trade Impacts on Water and Land Security in Iraq. Agronomy 2020, 10, 98.
34. Shea M. A., Zaljubovsky I. I., Wada M., and Inoue A., (1985) "A suggested standardized format for cosmic ray ground-level event data", 19th international cosmic ray conference (ICRC1985), La Jolla, United States. https://nts.nasa.gov/search.jsp
35. Poluianov S. V., Usoskin I. G., and Mishev A. L., (2017) "GLE and Sub-GLE Redefinition in the Light of High-Altitude Polar Neutron Monitors", Solar Physics, 292, 176. https://doi.org/10.1007/s11207-017-1202-4.
36. Usoskin I. G., Mursula K., Kangas J., and Gvozdevsky B., (2001) "On-Line Database of Cosmic Ray Intensities, Proceedings of International Cosmic Ray Conference (ICRC2001), (4pp).