# Latitude Distribution and N-S Asymmetry of GLE Event Source Locations during 1942–2024 (Postprint)

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## Abstract

We examined the heliolatitude distribution and North-South (N-S) asymmetry of Ground Level Enhancement (GLE) event source locations from 1942 to 2024, finding distinct patterns between the periods 1942–1979 and 1980–2024. Between 1942 and 1979, 33 GLE events were recorded: 5 from the southern hemisphere within [S3, S11] and 28 from the northern hemisphere within [N7, N37]. The southeast quadrant was devoid of any source locations for GLE events. 45.4% of the source locations of the GLE events were within the latitudinal range of [S15, N15]. The remaining source locations of the GLE events were distributed at latitudes above 15° in the northern hemisphere. Between 1980 and 2024, 43 GLE events were recorded: 25 from the southern hemisphere and 18 from the northern hemisphere, with all events above 30° latitude originating from the northern hemisphere. Approximately 44.2% of the source locations of the GLE events were distributed within the latitudinal band [S15, N15]. Over the period from 1942 to 2024, 44.7% within [S15, N15], 63.2% within [S20, N20], 80.3% within [S25, N25], 88.2% within [S30, N30], and 11.8% at latitudes above 30°. N-S asymmetry was significant at latitudes above 0°, 5°, 10°, 15°, 20° and 30°, with northern hemisphere dominance. Moreover, a strong inverse correlation exists between the number of GLE events from the northern and southern hemispheres at latitudes above 0°, 5°, 10°, 15°, 20°, 25° and 30°.

## Full Text

## Preamble

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# Latitude Distribution and N-S Asymmetry of GLE Event Source Locations during 1942–2024

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## Abstract

We examined the heliolatitude distribution and North-South (N-S) asymmetry of Ground Level Enhancement (GLE) event source locations from 1942 to 2024, finding distinct patterns between the periods 1942–1979 and 1980–2024. Between 1942 and 1979, 33 GLE events were recorded: 5 from the southern hemisphere within [S3, S11] and 28 from the northern hemisphere within [N7, N37]. The southeast quadrant was devoid of any source locations for GLE events. 45.4% of the source locations of the GLE events were within the latitudinal range of [S15, N15]. The remaining source locations of the GLE events were distributed at latitudes above 15° in the northern hemisphere. Between 1980 and 2024, 43 GLE events were recorded: 25 from the southern hemisphere and 18 from the northern hemisphere, with all events above 30° latitude originating from the northern hemisphere.

Approximately 44.2% of the source locations of the GLE events were distributed within the latitudinal band [S15, N15]. Over the period from 1942 to 2024, 44.7% within [S15, N15], 63.2% within [S20, N20], 80.3% within [S25, N25], 88.2% within [S30, N30], and 11.8% at latitudes above 30°. N-S asymmetry was significant at latitudes above 0°, 5°, 10°, 15°, 20° and 30°, with northern hemisphere dominance. Moreover, a strong inverse correlation exists between the number of GLE events from the northern and southern hemispheres at latitudes above 0°, 5°, 10°, 15°, 20°, 25° and 30°.

**Key words:** Sun: flares –Sun: coronal mass ejections (CMEs) –Sun: particle emission –(Sun:) sunspots

## 1. Introduction

When the Sun is not emitting very high-energy particles, the detectors on Earth' s surface primarily register galactic cosmic rays. However, when the Sun emits protons with energies exceeding 437 MeV, the flux of particles detected by ground-based instruments will experience a sudden increase followed by a decline. This phenomenon is known as a Ground Level Enhancement (GLE) event. It is important to note that ground-based detectors only record the secondary component resulting from the interaction between relativistic solar protons (RSPs) and the Earth' s atmosphere. The acceleration mechanisms of the solar energetic particles (SEPs) have been extensively studied by researchers (Reames 1999, 2013, 2020; Gopalswamy et al. 2002, 2012; Cane et al. 2003, 2006, 2007, 2010; Kallenrode 2003; Klecker et al. 2006, 2007; Ding et al. 2013, 2019; Qin et al. 2013; Qin & Wang 2015; Cliver 2016; Desai & Giacalone 2016; Papaioannou et al. 2016; Klein & Dalla 2017; Le & Zhang 2017; Le et al. 2017; Zhu et al. 2021; Ameri et al. 2024). A substantial body of literature has been dedicated to exploring the origins of RSPs (Cliver et al. 1982; Le et al. 2006; Reames 2009a, 2020; Firoz et al. 2010, 2011, 2019; Aschwanden 2012; Gopalswamy et al. 2012; Mewaldt et al. 2012; Moraal & McCracken 2012; Nitta et al. 2012; Miroshnichenko 2015; Ding et al. 2016; Kocharov et al. 2023; Waterfall et al. 2023). However, the origin of the RSPs is still an open question.

Due to the propagation of charged particles along interplanetary magnetic field lines, researchers place significant emphasis on the longitudinal distribution of GLE events. The longitudinal distribution of SEPs may reveal crucial information about the origins of RSPs (Le & Zhang 2017; Le et al. 2017; Cliver et al. 2020; Biji & Prince 2023). Consequently, several papers have been devoted to statistical analyses of the longitudinal distribution of SEPs and GLE events (Belov et al. 2010; Cliver et al. 2020; Le & Liu 2020; Le et al. 2021b).

A GLE event is categorized as one of the extreme solar events (Cliver et al. 2022). The impact of GLE events on space weather has been evaluated by some researchers (Shea & Smart 2012; Riley et al. 2018). A GLE event is typically triggered by a potent solar flare in conjunction with a high-energy coronal mass ejection (CME), both of which usually originate from the same active region (AR) on the Sun. To facilitate description, an AR that generated a GLE event is referred to as ARGLEs. It has been found that more ARGLEs came from the northern hemisphere (Le & Liu 2020).

According to Le et al. (2021a), 54.3% of ARGLEs were identified as super active regions, a concept that was defined by Chen et al. (2011). However, a statistical assessment of the significance of the North-South (N-S) asymmetry in the number of the GLE events with source locations in the two hemispheres has not yet been carried out. The N-S asymmetry in various types of solar activity is reflected in both their number and their latitudinal distribution across the two hemispheres. The latitudinal distribution and N-S asymmetry of the source locations of the GLE events reflect the patterns and laws governing solar activity. However, a statistical analysis of the latitudinal distributions and N-S asymmetry of GLE event source locations remains unexplored. Therefore, it is highly compelling to delve into the latitudinal distribution and N-S asymmetry of the source locations of GLE events.

The N-S asymmetry is evident in two ways: first, through the disparity in the number of GLE events originating from the northern and southern hemispheres, and second, through the uneven latitudinal distribution of the source locations of these GLE events. Is the N-S asymmetry of GLE event source locations in the two hemispheres significant, taking into account both the quantity of these source locations and their latitudinal distribution across both hemispheres? One of the motivations is to address these questions. The N-S asymmetry typically varies over time. Therefore, the N-S asymmetry of the source locations of the GLE events during different periods will also be assessed.

The article is organized as follows: Section 2 examines the heliolatitudinal distribution and N-S asymmetry of GLE event source locations. Section 3 is dedicated to discussion. The final section presents the summary and conclusion.

## 2. Heliolatitudinal Distribution and N-S Asymmetry of the Source Locations of the GLE Events

By integrating the 72 GLE events documented by Miroshnichenko (2015), the GLE events during solar cycles 21–23 compiled by Belov et al. (2010), some historic GLE events (Reames 2009b), and those occurring in solar cycle 23 summarized by Gopalswamy et al. (2012), alongside GLE data from the GLE Database, cosmic ray observations from NMDB, and the solar flare intensities and time information data since 1976 obtained from NOAA FTP, we have compiled a comprehensive list of 76 GLE events, which is presented in Table A1 in the appendix. Specifically, source locations for these events were identified as follows: GLE71 at N13W83 by Papaioannou et al. (2014), GLE72 at S08W88 by Reames (2009a), and GLE73 at S26W02 by Papaioannou et al. (2022). This compilation includes detailed information on the occurrence dates, corresponding solar flare intensities, and source locations of these events from 1942 to 2024, which is presented in Table A1 of the Appendix. Smoothed monthly mean sunspot numbers (SMMSNs) were accessible from the website at SILSO. By correlating the time information, the source locations of each GLE event, and the SMMSNs, the solar cycle distribution of the heliolatitude of the source locations of the GLE events from 1942 to 2024 is depicted in Figure 1.

As can be seen from Figure 1, ARGLEs in the southern hemisphere were rare before 1980. In contrast, a significant increase in ARGLEs is observed in the southern hemisphere after 1980. Evidently, the distribution patterns of GLE event source regions in the northern and southern hemispheres during 1942–1979 showed significant differences from those during 1980–2024. Consequently, we divided the period from 1942 to 2024 into two distinct periods: the first spanning from 1942 to 1979 December, and the second from 1980 January to 2024.

### 2.1. Distribution of GLE Event Source Locations During 1942-1979

Figure 2 displays the source locations of the GLE events between 1942 and 1979. During this period, a total of 33 GLE events were recorded, with 5 originating from the southern hemisphere and 28 from the northern hemisphere. The five GLE events in the southern hemisphere were confined to heliolatitudes between S3 and S11, while the 28 GLE events in the northern hemisphere were confined to heliolatitudes ranging from N7 to N35. It is evident that N-S asymmetry is significant. The pronounced N-S asymmetry observed in GLE event source locations is primarily attributed to those in the northern hemisphere, particularly at heliolatitudes above 11°, given that only four GLE events occurred at heliolatitudes below N12. A total of 15 GLE event source locations occurred within the heliolatitudinal range of [S15, N15], indicating that approximately 45.4% of all GLE events were produced by ARGLEs, which were found to be confined within the range of [S11, N15]. A noteworthy phenomenon depicted in Figure 2 is the absence of GLE event source locations in the southeast quadrant. The percentage of GLE events originating from the southern hemisphere was only about 15.2%. Consequently, 84.8% of the GLE events were sourced from the northern hemisphere of the Sun.

### 2.2. Distribution of GLE Event Source Locations During 1980-2024

The source locations of the GLE events during 1980-2024 are shown in Figure 3. The total count of GLE events depicted in Figure 3 is 43. A total of 18 GLE events were generated by ARGLEs in the northern hemisphere, while 25 GLE events originated from ARGLEs in the southern hemisphere. This distribution suggests that the southern hemisphere experienced more GLE events during this period. However, the N-S asymmetry is not significant. It was found that the source locations of 19 GLE events were confined within the heliolatitudinal range of [S15, N15]. Therefore, 44.2% of the source locations of the GLE events fell within this heliolatitudinal band. The number of source locations of the GLE events occurring within the heliolatitudinal band of [S20, N20] was 27, which represents 62.8% of the total GLE events.

### 2.3. Distribution of GLE Event Source Locations During 1942-2024

The source locations of the GLE events that occurred during 1942-2024 are shown in Figure 4. Within any specified heliolatitudinal range, we denote the number of GLE events with source locations occurring in the northern and southern hemispheres as Nn and Ns, respectively. The number of GLE events with source locations occurring across various heliolatitudinal ranges during 1942-2024 is presented in Table 1.

The percentages of GLEs with source locations occurring within various heliolatitudinal bands, as calculated, are presented in Table 2. As detailed in Table 1, the number of GLE events with source locations within the heliolatitudinal bands [S15, N15], [S20, N20], [S25, N25], and [S30, N30] were 34, 48, 61, and 67, respectively. With the total count of GLE events recorded between 1942 and 2024 being 76, this means that 44.7%, 63.2%, 80.3%, and 88.2% of the source locations of the GLE events were confined within the heliolatitudinal ranges [S15, N15], [S20, N20], [S25, N25], and [S30, N30], respectively. The results showed that less than 45% of the GLE events were distributed within 15° of the solar equator. A total of nine GLE events with source locations at heliolatitudes above 30° were recorded, all of which were confined to the northern hemisphere.

The binomial formula (Larson 1982) is employed to calculate the probability of achieving any specific distribution of n objects across two categories. This formula is extensively utilized to ascertain the statistical significance of the N-S asymmetry, as evidenced by various studies (e.g., Li et al. 2002; Joshi & Joshi 2004; Carbonell et al. 2007). In this study, the two classes are defined by the counts of GLE events with source locations occurring in the northern and southern hemispheres. The binomial formula, which is pivotal for our analysis, is given by: the probability of obtaining more than d objects in class 1. If the probability P(>d) is less than 5%, then the N-S asymmetry is considered significant. If 5% < P(>d) < 10%, the N-S asymmetry is regarded as marginally significant. A value of P(>d) greater than 10% suggests that the N-S asymmetry is statistically insignificant. The probabilities P(>d) for the different latitudinal bands, as indicated in Table 2, have been computed and are detailed in the fourth column of Table 2.

As shown in Table 2, the N-S asymmetries in the number of GLE events, with sources located in the two hemispheres, are significant at latitudes exceeding 0°, 5°, 10°, 15°, 20°, and 30°. A chi-squared ( $^{2}$) test was conducted on the counts of GLE events originating from the northern and southern hemispheres at latitudes above certain thresholds. The resulting p-values from these tests were compiled in the final column of Table 2. The results consistently revealed p-values below 0.05, underscoring a significant inverse correlation between the occurrence of GLE event source locations in the northern and southern hemispheres at latitudes above 0°, 5°, 10°, 15°, 20°, 25°, and 30°. This indicates that the numbers of GLE events with source locations at these latitudes in the two hemispheres are anti-correlated.

## 3. Discussion

The shocks driven by CMEs are involved in or dominate the acceleration of relativistic solar protons that lead to GLE events. Since charged particles propagate along interplanetary magnetic field lines, it is reasonable that the source regions of the vast majority of GLE events appear in the western hemisphere. It should be noted that an extreme geomagnetic storm is caused by the interaction of a CME-driven shock and the CME itself with the magnetosphere upon reaching it. It has been found that the source regions of 90% of the great geomagnetic storms (Dst $\leq -200$ nT) are concentrated within the longitudinal area [E45, W45] (Le et al. 2021c). Because the propagation path of CMEs in interplanetary space is completely different from that of charged particles, the comparison of the longitude distribution of the source locations of GLE events and the source locations of extreme geomagnetic storms is not physically meaningful. However, since both GLE events and extreme geomagnetic storms are caused by CMEs, and some CMEs that cause GLE events also lead to extreme storms (Le et al. 2021b), it is physically meaningful to compare the latitude distributions of CMEs causing GLE events and those causing extreme geomagnetic storms.

Solar sunspot activity was dominant in the northern hemisphere during solar cycles 14–20. However, solar activity has been found to dominate in the southern hemisphere during solar cycles 21–23 (Li et al. 2002; Veronig et al. 2021), indicating that during solar cycles 14–20, solar activity was predominantly in the northern hemisphere, and starting from cycle 21, it shifted to being mainly in the southern hemisphere. We found a significant disparity in the distribution of the GLE event source locations across the northern and southern hemispheres. The period from 1942 to 1979 exhibited distinct patterns compared to the years from 1980 to 2024. This indicates that 1980 marks a significant turning point in solar activity, as manifested by solar activities that can lead to GLE events. Prior to 1980, the source locations of GLE events were predominantly in the northern hemisphere, while the southern hemisphere experienced more GLE events during the period from 1980 to 2024.

## 4. Summary and Conclusion

We conducted a study on the latitudinal distribution relative to the solar equator, as well as the N-S asymmetry of GLE events from 1942 to 2024. The total number of GLE events recorded during this period was 76. We discovered a significant difference in the distribution of GLE event source locations between two distinct periods: 1942–1979 and 1980–2024. A total of 33 GLE events were recorded between 1942 and 1979, whereas 43 GLE events occurred during the period from 1980 to 2024.

For the GLE events that occurred between 1942 and 1979, only five originated from the southern hemisphere, and all of these events were confined within the heliolatitudinal band ranging from S3 to S11. Within the heliolatitudinal band spanning from S11 to N11, no significant N-S asymmetry was observed. However, the source locations of GLE events at latitudes above 11° were found exclusively in the northern hemisphere. A noteworthy phenomenon was the absence of the source locations of GLE events in the southeast quadrant. A total of 45.4% of the source locations for GLE events were confined within the heliolatitude band that spans from S15 to N15.

Out of the 43 GLE events recorded between 1980 and 2024, 25 originated from the southern hemisphere and 18 from the northern hemisphere. This suggests that the southern hemisphere experienced more GLE events. However, N-S asymmetry was not significant. Notably, the source locations of all GLE events that occurred at heliolatitudes above 30° were only located in the northern hemisphere. A total of 44.2% of the GLE events had their source locations confined within the latitudinal band extending from S15 to N15.

Between 1942 and 2024, the proportions of GLE events originating within specific heliolatitudinal bands were as follows: 44.7% within [S15, N15], 63.2% within [S20, N20], 80.3% within [S25, N25], 88.2% within [S30, N30], and 11.8% at latitudes above 30°. There is a significant N-S asymmetry in the number of GLE events at heliolatitudes above 0°, 5°, 10°, 15°, 20°, and 30°. Furthermore, a strong inverse relationship is observed between the number of GLE events in the northern hemisphere at these latitudes and those in the southern hemisphere at latitudes above 0°, 5°, 10°, 15°, 20°, 25°, and 30°.

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Smoothed monthly mean sunspot numbers were available from the website at https://www.sidc.be/SILSO/datafiles. Solar flare data can be accessed via the NOAA National Geophysical Data Center' s website at ftp://ftp.ngdc.noaa.gov/STP/space-weather/solar-data/solar-features/solar-flares/x-rays/goes/xrs/. The time and source location information for the solar proton event associated with GLE74 were retrieved from the weekly report prf2541.pdf, which can be accessed through the website ftp://ftp.swpc.noaa.gov/pub/warehouse.

## Appendix

The information for the GLE events. For each GLE event, the date of occurrence, the derived B0 angle, the source location, and associated flare information are all listed in detail. See Table A1 for specifics.

**Table A1. List of GLE Events during 1942-2024**

| GLE No. | Date (YYYY/mm/dd) | B0 Angle | Flare Location | Flare Intensity |
|---|---|---|---|---|
| 1 | 1942/02/08 | -6.52 | N07E04 | 2B/X2.0 |
| 2 | 1942/03/07 | -7.25 | N07W90 | 3B/X5.0 |
| 3 | 1946/07/05 | -6.15 | N22E15 | 3B/X4.0 |
| 4 | 1949/11/19 | -3.76 | S03W72 | 3B/X4.0 |
| 5 | 1956/02/03 | -5.72 | N23W80 | 2B/X1.0 |
| 6 | 1956/08/31 | -5.74 | N15E15 | 2B/X2.0 |
| 7 | 1959/07/17 | -7.17 | N16W31 | 3B/X2.0 |
| 8 | 1960/05/04 | -6.63 | N13W90 | 2B/X1.0 |
| 9 | 1960/09/03 | -5.48 | N18E88 | 2B/X1.0 |
| 10 | 1960/11/12 | -4.26 | N27W04 | 2B/X1.0 |
| 11 | 1960/11/15 | -4.13 | N25W35 | 3B/X1.0 |
| 12 | 1960/11/20 | -3.54 | N28W112 | 1B/C6.0 |
| 13 | 1961/07/18 | -5.92 | S07W59 | 2B/X2.5 |
| 14 | 1961/07/20 | -3.17 | S06W90 | 2B/M1.3 |
| 15 | 1966/07/07 | -0.00 | N35W48 | 2B/X3.1 |
| 16 | 1967/01/28 | -6.87 | N22W150 | 2B/X4.5 |
| 17 | 1967/01/28 | -1.88 | N22W150 | 1B/X2.8 |
| 18 | 1968/09/29 | - | N17W51 | -/C2.3 |
| 19 | 1968/11/18 | - | N21W87 | 1B/X2.6 |
| 20 | 1969/02/25 | - | N13W37 | 2N/X20.0 |
| 21 | 1969/03/30 | - | N19W103 | 1B/X9.8 |
| 22 | 1970/01/24 | - | N18W49 | 4B/X13.0 |
| 23 | 1971/09/01 | - | S11W120 | 2B/X2.9 |
| 24 | 1972/08/04 | - | N14E08 | 3B/X5.7 |
| 25 | 1972/08/07 | - | N14W37 | 3B/X3.2 |
| 26 | 1973/04/29 | - | N14W73 | 2B/X5.5 |
| 27 | 1976/04/30 | - | S09W47 | - |
| 28 | 1977/09/19 | - | N08W58 | - |
| 29 | 1977/09/24 | - | N10W120 | - |
| 30 | 1977/11/22 | - | N24W40 | - |
| 31 | 1978/05/07 | - | N23W72 | - |
| 32 | 1978/09/23 | - | N35W50 | - |
| 33 | 1979/08/21 | - | N15W38 | - |
| 34 | 1981/04/10 | - | N07W36 | - |
| 35 | 1981/05/10 | - | N03W75 | - |
| 36 | 1981/10/12 | - | S18E30 | - |
| 37 | 1982/11/26 | - | S12W87 | - |
| 38 | 1982/12/07 | - | S19W86 | - |
| 39 | 1984/02/16 | - | S16W94 | - |
| 40 | 1989/07/25 | - | N25W84 | - |
| 41 | 1989/08/16 | - | S18W84 | - |
| 42 | 1989/09/29 | - | S24W100 | - |
| 43 | 1989/10/19 | - | S27E10 | - |

| GLE No. | Date (YYYY/mm/dd) | B0 Angle | Flare Location | Flare Intensity |
|---|---|---|---|---|
| 44 | 1989/10/22 | - | S27W31 | - |
| 45 | 1989/10/24 | - | S30W57 | - |
| 46 | 1989/11/15 | - | N11W28 | - |
| 47 | 1990/05/21 | - | N35W36 | - |
| 48 | 1990/05/24 | - | N33W78 | - |
| 49 | 1990/05/26 | - | N35W103 | - |
| 50 | 1990/05/28 | - | N35W120 | - |
| 51 | 1991/06/11 | - | N32W17 | - |
| 52 | 1991/06/15 | - | N36W70 | - |
| 53 | 1992/06/25 | - | N09W67 | - |
| 54 | 1992/11/02 | - | S25W100 | - |
| 55 | 1997/11/06 | - | S18W63 | - |
| 56 | 1998/05/02 | - | S15W15 | - |
| 57 | 1998/05/06 | - | S11W65 | - |
| 58 | 1998/08/24 | - | N35E09 | - |
| 59 | 2000/07/14 | - | N22W07 | - |
| 60 | 2001/04/15 | - | S20W85 | - |
| 61 | 2001/04/18 | - | S23W117 | - |
| 62 | 2001/11/04 | - | N06W18 | - |
| 63 | 2001/12/26 | - | N08W54 | - |
| 64 | 2002/08/24 | - | S03W81 | - |
| 65 | 2003/10/28 | - | S16E08 | - |
| 66 | 2003/10/29 | - | S15W02 | - |
| 67 | 2003/11/02 | - | S14W56 | - |
| 68 | 2005/01/17 | - | N15W25 | - |
| 69 | 2005/01/20 | - | N14W61 | - |
| 70 | 2006/12/13 | - | S06W23 | - |
| 71 | 2012/05/17 | - | N11W76 | - |
| 72 | 2017/09/10 | - | S08W88 | - |
| 73 | 2021/10/28 | - | S26W02 | - |
| 74 | 2024/05/11 | - | S15W45 | - |
| 75 | 2024/06/08? | - | S18W53 | - |
| 76 | 2024/11/21 | - | S08E31 | - |

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