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# Variability in Solar Proton Events (SPEs) associated with GLEs during the last 28 years (1996-2024)

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## Abstract

This study investigates major solar proton events (SPEs) and associated ground level enhancements (GLEs) over the complete solar cycles 23, 24, and the rising phase of solar cycle 25 (1996-2024). The analysis reveals that GLEs predominantly occur during peak solar activity years (3-8). Solar cycle 23 had 16 GLEs, while cycle 24 only had 2. A notable GLE, GLE73, occurred in the rising phase of cycle 25, indicating possible higher activity during the cycle's peak. The response of neutron monitors at different locations is also discussed, suggesting a trend of decreasing SPEs and GLEs over cycles 24 and 25, except for an unexpected rise in cycle 25's initial phase.

## 1. Introduction

When relativistic solar protons (RSPs) interact with the Earth's atmosphere, they cause an atmospheric cascade, increasing cosmic ray intensity detected by ground-based neutron monitors [1]. GLEs are significant events characterized by a sudden increase in cosmic ray counts [2]. Previous studies have noted varying SPE distributions across solar cycles, with higher occurrences during peak solar activity. A total of 73 GLEs have been recorded since 1942, with the most recent being GLE73 on October 28, 2021. GLEs can be categorized into true GLEs, sub-GLEs, and sub-sub-GLEs, depending on their intensity and energy levels.

## 2. Data Sources

This study uses data from the SOHO LASCO catalog for major solar proton events, the OMNI web database for soft X-ray data, and the Oulu neutron monitor for ground-level enhancement data. Data from 1996 to 2022 were filtered to identify significant GLEs related to SPEs, coronal mass ejections (CMEs), and soft X-rays, and their latitudinal locations and class were compared across solar cycles 23, 24, and 25.

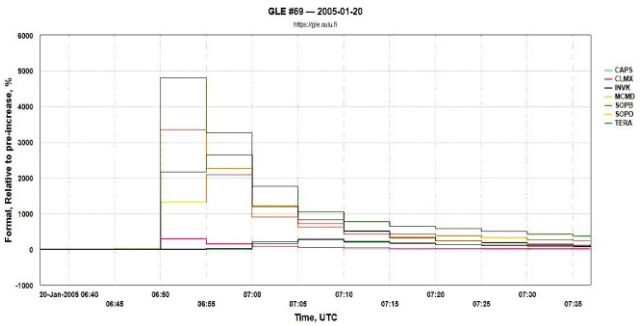
## 3. Solar Radiation vs GLEs

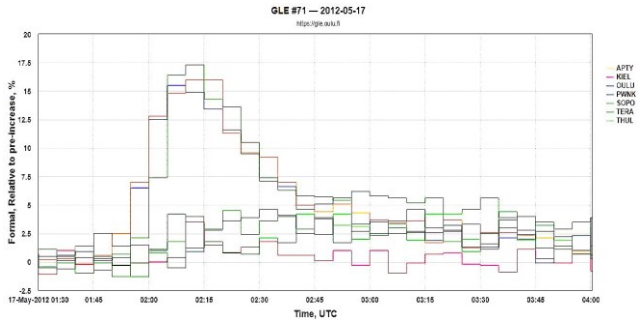
Solar eruptions produce high-energy particles known as solar energetic particles (SEPs), which can cause GLEs when they reach the Earth [2,3]. GLEs are defined by a significant increase in neutron monitor counts, confirmed by space-borne instruments detecting a concurrent rise in proton flux. A total of 73 GLEs have been recorded, with varying definitions and thresholds over time.

## 4. Ground Level Enhancements in Solar Cycles 23, 24 and 25

Figure 1 shows the major GLEs of SC23, SC24 and most prominent one of SC25. Solar cycle 23 observed 16 GLE events with intensities ranging from -3% to 269%, while cycle 24 had only 2 events. The most intense GLE of cycle 23, GLE69, occurred on January 20, 2005, with a relative increase of 4808.95% on the Oulu neutron monitor. In cycle 24, GLE events on May 17, 2012, and September 10, 2017, were observed, both associated with high-speed CMEs and significant solar flares.

On October 28, 2021, GLE73 was detected, marking the first GLE of solar cycle 25. The event was associated with an X1.0 class flare and observed by multiple neutrons monitors worldwide, with the highest intensity recorded at the Antarctic plateau. This unexpected rise in GLE activity during the cycle's initial phase suggests the potential for more significant events as cycle 25 progresses.



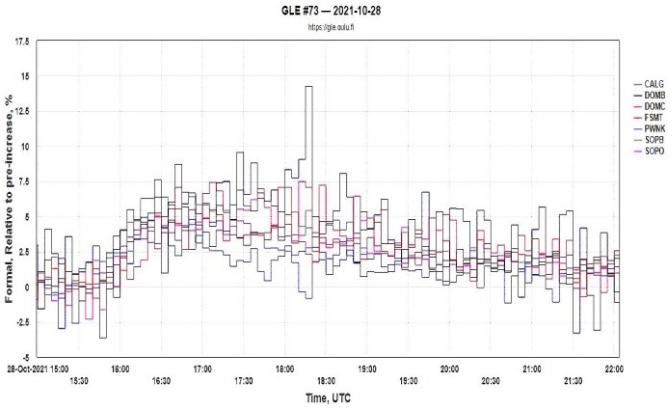



**Figure 1.** Formal, Relative to pre-increase (%) of GLE 69 **(top)** (2005, January 20), Formal, Relative to pre-increase (%) of GLE 71 **(middle)** (2012, May 17), Formal, Relative to pre-increase (%) of GLE 73 **(bottom)** (2021, October 28) for seven major Neutron monitors.

## 5. Conclusion

The study concludes that solar proton events and GLEs have decreased in frequency and intensity from solar cycle 23 to 24, with an unexpected rise observed in the early phase of cycle 25. This trend may indicate a higher activity level during the peak of cycle 25. Further analysis of SEPs and GLEs is needed to understand the dynamics and potential impacts of future solar cycles on space weather and related phenomena.

## 6. Acknowledgements

We acknowledge the use of data obtained from the SOHO LASCO catalog (https://cdaw.gsfc.nasa.gov/CME_list/sepe/) and OMNI web database (https://omniweb.gsfc.nasa.gov/form/dx1.html). Ground-level enhancement data is obtained from the Oulu neutron monitor (https://gle.oulu.fi/#/). PS is thankful to the University Grants Commission (UGC), India, for providing partial financial support as JRF/SRF.

## 7. References

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