Indonesian Journal of Aerospace Vol. 22 No. 2 Desember 2024 : pp 95 – 102 (Juangsih et al.)
DOI: 10.59981/ijoa.2024.2989
https://ejournal.brin.go.id/ijoa/

The Occurrence Of Geomagnetic Storm In Solar Cycles 23 And 24 And Their Correlation With Cycle Peaks

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Received: 20-12-2023. Accepted: 15-07-2024. Publishied: 20-05-2025

Abstract

The 23rd solar cycle occurred from 1996 to 2008, while the 24th solar cycle occurred from 2009 to 2020. Throughout the cycles there were various solar activities that caused geomagnetic storm such as high speed stream (HSS), co-rotating interaction region (CIR), and coronal mass ejection (CME). By using Disturbance storm time (Dst) index, we identified 243 storms during cycle 23 and 149 storms during cycle 24. The distribution of geomagnetic storms corresponds to the distribution of the solar cycle based on sunspot numbers. The cycle 23 exhibited higher activity with 84 strong to extreme storms compare to cycle 24 which had 22 strong to very strong storms. In both cycles, 65% moderate geomagnetic storms were caused by the high speed stream, whereas 85% of strong geomagnetic storms were caused by CMEs. In this study, both cycles exhibit distinct characteristic in producing geomagnetic storms. The low or high maximum phase of a cycle is not associated with the frequency occurrence of strong to extreme geomagnetic storms; both cycles show comparable results in this regard. However a longer declining phase of solar cycle has more impact on production of more moderate storms.

Keywords: *Geomagnetic Storm, Dst Index, Solar Cycle, Coronal Mass Ejection*

1. Introduction

Geomagnetic activity on Earth is commonly associated with CME events or high-speed solar wind flows (Yatini, 2010). Geomagnetic activity occurs due to physical processes in the Earth's magnetosphere. A common cause of geomagnetic phenomena is the flow of energy from the Sun to Earth via the solar wind, which interacts with the magnetosphere and sometimes causes geomagnetic disturbances. When the geomagnetic disturbances reach a certain level, it can cause geomagnetic storms.

In general, geomagnetic storms are caused by unusual conditions in the interplanetary magnetic field (IMF) and emissions of solar wind caused by various types of solar activity. The solar activities that cause magnetic storms are high-speed solar wind streams (HSS), co-rotating interaction regions (CIRs), and coronal mass ejections (CMEs). (Gonzales, 1994). Studies have shown that CMEs play an important role in disturbances in interplanetary space and may be the cause of geomagnetic storms. (Gosling, 1993)

Geomagnetic disturbances are driven by the interaction of the solar wind with the magnetosphere and the magnitude of the disturbances depends on the parameters of the solar wind. The study of geomagnetic field disturbance is important in understanding the dynamics of the Sun-Earth environment, and furthermore, the impact of geomagnetic storms can cause power outages, satellite damage, communication disruptions, and navigation disturbances. (Rathore, 2012)

The Solar cycle 23 and 24 as the most recent cycles, were identified as having the longest and lowest solar minimum period between them, following one previously identified as a 'deep minimum' between cycles 14 and 15 (Russell et al. 2010; Richardson and Cane 2012a; Richardson 2013; McComas et al. 2013).

This study analyzes geomagnetic storms and their sources during the 23rd and 24th solar cycles. The sources of the storms are identified through an analysis of changes in interplanetary medium parameters. By examining variations in these parameters, we aim to elucidate the relationship of geomagnetic storm events to solar activity cycles.

2. Data And Methodology

The period of the 23rd solar cycle is from August 1996 to December 2008, while the 24th solar cycle is from January 2009 to December 2020. The geomagnetic storms were classified into five categories based on the Dst index according to the criteria outlined by Loewe and Prolss (1997). The classification scheme consists of weak (-50 < Dst ≤ -30 nT), moderate (-100 < Dst ≤ -50 nT), strong (Dst ≤ -100 nT), very strong (Dst ≤ -200 nT), and extreme (Dst ≤ -350 nT) storms. The Dst index is available on the website of the World Data Center for Geomagnetism, Kyoto, Japan.

The interplanetary medium parameters used in this study are velocity and density of solar wind, and southward interplanetary magnetic field (Bz) obtained from Omni Web Data https://omniweb.gsfc.nasa.gov. To verify one of the solar sources of geomagnetic storms, it is necessary to acquire CME data obtained from the website https://cdaw.gsfc.nasa.gov/CME_list/. Yearly sunspot data used in this study are derived from monthly sunspot number data obtained from the World Data Center SILSO https://wwwbis.sidc.be/silso/.

To analyze the source of geomagnetic storms and their relationship with the solar cycle, we initially identified geomagnetic storms with a Dst index below -50 nT during the 23rd and 24th solar cycles, followed by classification based on the criteria established by Loewe and Prolss (1997) Guarnieri et al. 2006 examined the Dst index response under varying conditions during High-Intensity, Long-Duration Continuous AE Activity (HILDCAA) events for geomagnetic storms caused by Interplanetary Coronal Mass Ejections (ICMEs) and Co-rotating Interaction Regions (CIRs). The geomagnetic storm caused by ICME is usually preceded by a sudden increase called sudden storm commencement. Meanwhile, CIR-driven storms exhibit a gradual initial phase. The differences are caused by different mechanisms of solar origin phenomena influencing changes in the interplanetary parameters such as solar wind speed, density, temperature, and the interplanetary magnetic field. Those changes affected how the particles and energy were transported from solar origin to the magnetosphere and recorded on the Dst index as the initial, main, and recovery phases of geomagnetic storms (Gonzalez, et.al., 1994; Gonzalez, et.al., 1999; Clauer, 2006). By utilizing the characteristics of Dst index responses and changes in interplanetary parameters associated with various solar phenomena, we can identify the causes of geomagnetic storms during the 23rd and 24th solar cycles and then analyze their relationship with the solar cycle.

3. Result And Discussions

The rising phase of 23 solar cycle lasted for nearly 4 years until it reached its maximum, whereas the 24 cycle took about 2 years. The declining phase of both cycles were lasted about 7 years. Both cycles exhibited double peaks, but the peaks of 24 cycle were lower than those of 23 cycle.

From August 1996 to December 2020, 392 geomagnetic storms with Dst index ≤ -50 nT were identified. Figure 3-1 shows the occurrence number of geomagnetic storms with Dst index ≤ -50 nT and the annual average sunspot number. From the figure, it can be observed that the geomagnetic activity occurrence is almost proportional to the solar activity. When the solar activity is minimum, the incidence of geomagnetic activity is also minimum. On the contrary, when there is an increase in solar activity, geomagnetic activity is also increase, leading to a higher frequency of geomagnetic storms.

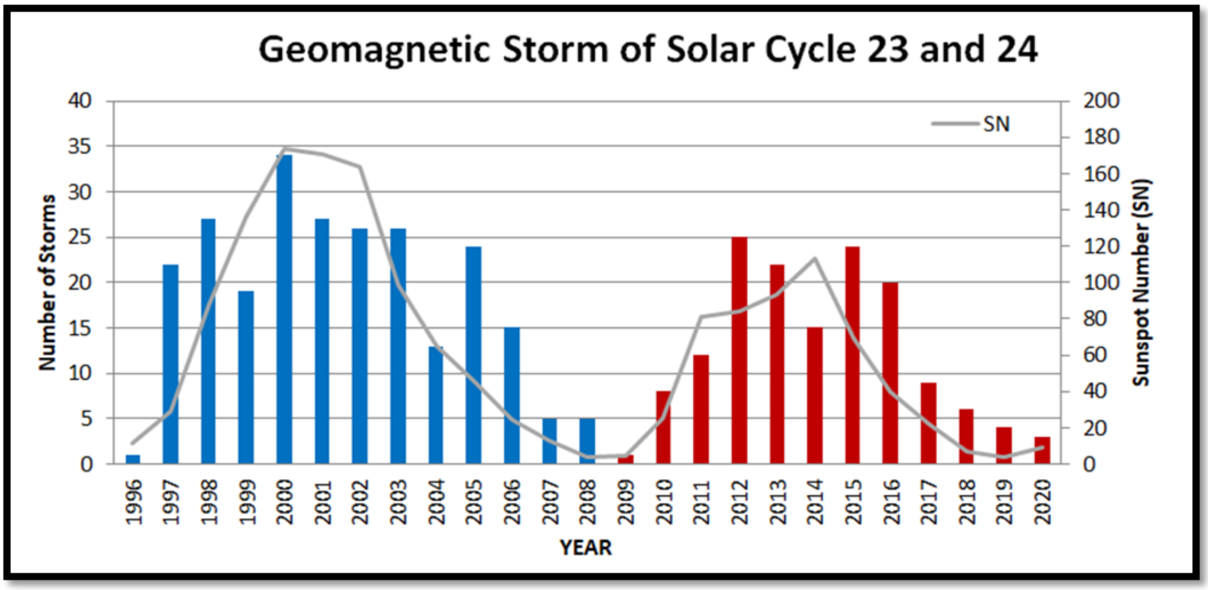

Figure. 3-1: The geomagnetic storm events distribution number in cycle 23 (blue bars) and cycle 24 (red bars). The gray line is the annual average sunspot number.

We have classified the geomagnetic storms and identified their originating source as shown in Table 3-1. In the period of cycles 23 and 24, there were 392 geomagnetic storm events. In cycle 23 there were 243 storms classified as 159 moderate storms, 68 strong storms, 12 very strong storms, and 4 extreme storms. Around 65% are classified as moderate storms, while the remaining are categorized as strong to extreme storms. The source of the storms was identified as 14 caused by CIR, 120 HSS, and 109 CME.

Cycle 24 was less active than cycle 23, resulting in fewer storms as well. Sawadogo, 2022 suggested that the earth's atmosphere was under the influence of quiet solar wind conditions and the long and low minimum following cycle 23 caused cycle 24 less active. There were 149 geomagnetic storm events with a classification of 127 moderate storms around 85% of total incidence, 20 strong storms, 2 very strong storms, and no extreme storms. The storms caused by CIR were 6 events, HSS 79 events, and CME 64 events. HSS produced the most geomagnetic storms on cycles 23 and 24, about 50.5%.

Table 3-1: List of 392 geomagnetic storms and their sources

	Events	Moderate	Strong	Very Strong	Extreme	CIR	HSS	CME
Cycle 23	243	159	68	12	4	14	120	109
Cycle 24	149	127	20	2	-	6	79	64
Total	392	286	88	14	4	20	199	173

As mentioned by Gosling (1993), the main causes of geomagnetic storms are CME, HSS, and CIR. Figure 3-2 shows the distribution number of geomagnetic storm events caused by CME, HSS, and CIR during the 23rd and 24th cycle. The frequency of geomagnetic storms caused by CMEs follows the solar cycle activity. The higher the solar activity, the higher of frequency occurrence of the geomagnetic storms caused by CME. Conversely, the lower the solar activity, the lower the frequency of geomagnetic storms caused by CME. The highest number of CME events occurred in 2001, which corresponds to the 23rd solar cycle peak. However, the largest geomagnetic storm occurred in 2003 and was caused by CME. There were 110 CME occurrences (45%) in cycle 23 and 64 occurrences (43%) in cycle 24. In cycle 24, the most CMEs occurred in 2012, while the peak of solar activity occurred in 2014.

In contrast to CMEs, when solar activity begins to decline, the incidence of HSS remains high. Even when the Sun was at its minimum, in 2007-2008, the incidence of storms caused by HSS was high. This was mentioned by Gonzales et al. (1999), that HSS originating from the Sun's coronal holes are more frequent during the declining phase of the solar cycle. During cycle 23, there were 118 geomagnetic storms caused by HSS, or about 49%. While during cycle 24, there were 80 storms, or about 54%.

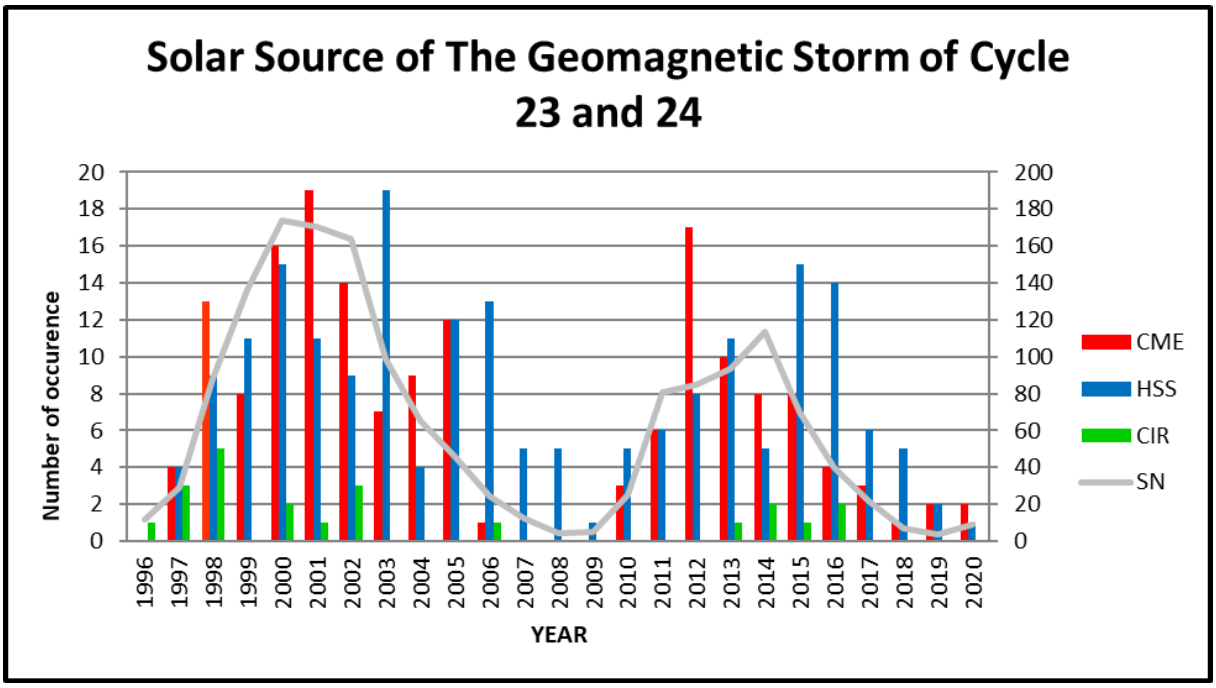

Figure 3-2: Source geomagnetic storms from cycles 23 and 24

CIR is the least common source of storms. CIR occurs when the fast solar wind stream interacts with the surrounding slow stream in low and middle-latitude regions of the heliosphere (Heber, et.al., 1999). For cycle 23 there were 23 CIR events or 6%. And in cycle 24 there were 4 CIR events or 3%. (Figure 3-3.)

During cycle 23 and 24 as shown in Table 3-2, there were 4 extreme geomagnetic storms and 14 very strong geomagnetic storms, all attributed to CME. Strong storms caused by CME occurred 76 times constituting 85% of total occurrence. While strong storms caused by HSS and CIR were observed 6 times each, accounting for 8% and 7% respectively. Moderate storms were predominantly caused by HSS with 193 storm events or 68%. The results show prevalence of CME as major drivers strong to extreme geomagnetic storms, while HSS as dominant cause of moderate storms. This results in moderate geomagnetic storms as dominant storm level for both cycles, as HSS is common features during rising and declining phase of solar cycle and it persist even though they are not as intense as the rising and declining phase.

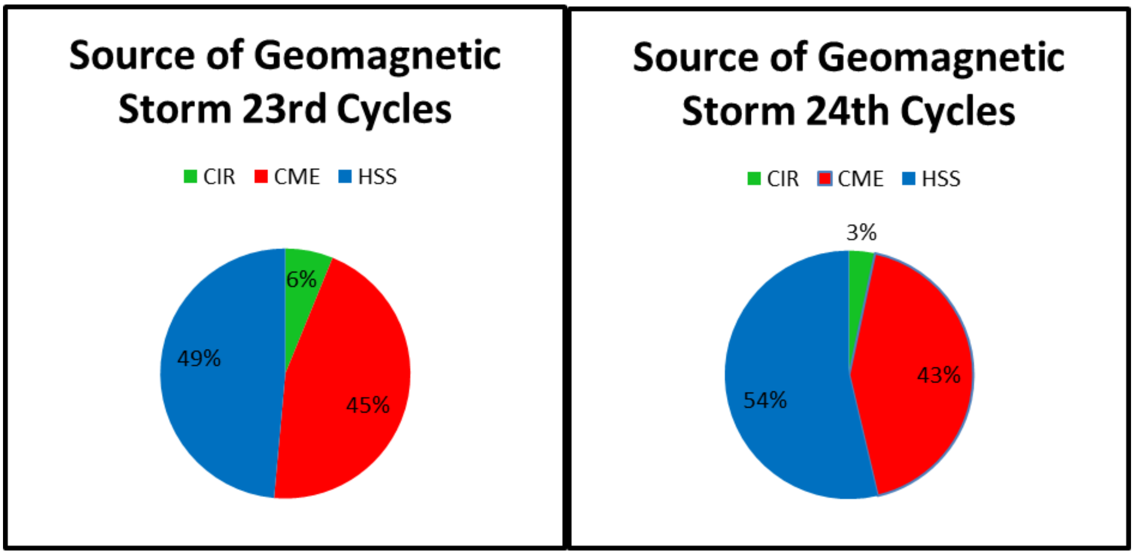

Figure 3-3: Pie chart Source geomagnetic storms from cycles 23 and 24

Table 3-2: Storm classification and origin

Storm	Source	Total Number of Events	Number of Events for Cycle-23	Number of Events for Cycle-24
Extreme	CME	4	4	-
Very Strong	CME	14	12	2
Strong	CME	76	58	18
	HSS	6	6	-
	CIR	6	4	2
Moderate	CME	79	35	44
	HSS	193	114	79
	CIR	14	10	4

Table 3-3 shows the largest storms during cycles 23 and 24. In cycle 23, the largest geomagnetic storm occurred on November 20, 2003 with an intensity of -422 nT and was an extreme storm. The maximum solar wind speed reached 738 km/s and the density reached 30 N/cm3. The minimum North-South interplanetary magnetic field (Bz) was -44 nT. The cause of this extreme storm was a CME that occurred on November 18, 2003 at 08:50 UT. The CME was a Halo CME type IV, 360° angular width, with a speed of 1660 km/s.

During cycle 24 no extreme storms occurred, so the largest was a very strong storm that occurred on March 17, 2015 with an intensity of -222 nT (Table 3-3). This event is referred to as St.Patrick's Day geomagnetic storm. The cause of this strong storm was a CME that occurred on March 15, 2015 at 01:48 UT. The CME was a Halo CME type IV, 360° angular width, with a speed of 719 km/s.

Table 3-3: The greatest geomagnetic storm on 23 and 24 cycle

	Solar Cycle 23	**Solar Cycle 24**
Date	20 November 2003	17 March 2015
Peak of the storm (Dst index)	-422 nT	-222 nT
Speed	738 km/s	668 km/s
Density of solar wind	30 N/cm^3	20 N/cm^3
Bz	-44 nT	-20 nT

Conclusion

Geomagnetic storms are correlated with the 11-year solar cycle. Solar cycle 23 has more geomagnetic storms than cycle 24 because cycle 23 has more sunspot numbers than cycle 24, means a higher potential to generate strong solar activity that could drive geomagnetic disturbances. The highest number of geomagnetic storms for cycle 23 occurred in 2000 while for cycle 24 it occurred in 2012. 68% of moderate geomagnetic storms are caused by the High Speed Stream. And 85% of strong geomagnetic storms are caused by CMEs.

Strong to extreme geomagnetic storms predominantly caused by CMEs. while geomagnetic storm events caused by HSS which is originating from the Sun's corona hole are more frequent during declining phase of the solar cycle. Based on these results, the 23rd and 24th solar cycle have distinct characteristic in producing geomagnetic storms. Whether characterized by a high maximum or low maximum cycle the strong to extreme geomagnetic storms has a comparable incidence, constituting 45% and 43% of both cycles respectively. However, there is a notable difference concerning moderate storms. During cycle 23 there was 65% of moderate storms incidence whereas in cycle 24 it reached 85% of total storm incidence. This variation may be attributed to a more sloping of declining phase observed in cycle 24 compared to cycle 23, indicating longer duration of declining phase on cycle 24. This phase is predominantly influenced by HSS which are the primary source of moderate storms. Consequently, this results in an increased occurrence rate of moderate storm on cycle 24. Thus, by estimating the solar cycle pattern in advance, it becomes possible to anticipate the frequency of moderate and strong to extreme storms beforehand.

The largest storm of both cycles occurred during declining phase, not far from the peak reached in each cycle. An extreme geomagnetic storm in cycle 23 occurred on November 20, 2003 while in cycle 24 a very strong storm occurred on March 17, 2015.

Acknowledgements

The authors would like to thank WDC Geomagnet-Kyoto for providing the Dst Index data, NASA Omni Web for providing data on solar wind parameters, SOHO LASCO for providing CME data. And thanks to the Editorial Team of the Aerospace Science Journal.

References

Wu, CC., Liou, K., Lepping, RP., Hutting, L., Plunkett, S., Howard, RA., Socker, D., et.al., 2016. *The first super geomagnetic storm of solar cycle 24: "The St. Patrick's day event (17 March 2015)"*, Earth, Planet, and Space, DOI 10.1186/s40623-016-0525-y.

Clauer, CR., 2006. *The geomagnetic storm-time response to different solar wind driving conditions*, in The Solar Influence on the Heliosphere and Earth's Environment: Recent Progress and Prospects—Proceedings of the ILWS Workshop

Loewe, A., and Prolss, GW., 1997. *Classification and mean behavior of magnetic storms,* Journal of Geophysical Research 102.14209-1421.

Gonzalez, WD., Joselyn, JA., Kamide, Y., Kroehl, HW., Rostoker, G., Tsurutani, BT., Vasyliunas, VM., 1994. *What Is A Geomagnetic Storms?* , J. Geophys. Res. 99, 5771.

Gonzalez, WD., Tsurutani, BT., Gonzalez, ALC., 1999. *Interplanetary Origin Of Geomagnetic*

Storms, Space Science Reviews, 88, 529–562, DOI 10.1023/A:1005160129098.

Gosling JT., 1993. *Coronal Mass Ejections: The Link Between Solar And Geomagnetic Activity* *Physics of Fluids B: Plasma Physics 5, 2638, AIP Physics of Plasmas

Guarnieri, FL., Tsurutani, BT., Gonzalez, WD., Gonzalez, ALC., Grande, M., Soraas, F., and Echeer, E., 2006. *ICMEE and CIR storms with particular emphases on HILDCAA events*, in The Solar Influence on the Heliosphere and Earth's Environment: Recent Progress and Prospects—Proceedings of the ILWS Workshop

Heber B., Sanderson T.R., Zhang M., 1999, *Corotating Interaction Region, Advance in Space Research*, Pages 567-579, https://doi.org/10.1016/S0273-1177(99)80013-1

McComas DJ, Angold N, Elliott HA, Livadiotis G, Schwadron NA, Skoug RM, Smith CW., 2013. *Weakest solar wind of the space age and the current "Mini" solar maximum*. Astrophys J. doi:10.1088/0004-637X/779/1/2

Rathore BS., Kaushik, SC., Bhadoria, RS., Parashar, KK., Gupta, DC. 2012. *Sunspots and geomagnetic storms during solar cycle-23*, Indian J Phys DOI 10.1007/s12648-012-0106-2

Richardson IG., 2013. *Geomagnetic activity during the rising phase of solar cycle 24*. J. Space Weather Space Clim. 3:A08. doi:10.1051/swsc/2013031

Richardson IG, and Cane HV., 2012a. *Solar wind driver of geomagnetic storms during more than four solar cycles*. J. Space Weather Space Clim 2:A01. doi:10.1051/swsc/2012001

Russell, CT., Luhmann, JG., and Jian, LK., 2010. *How unprecedented a solar minimum?* Rev. Geophys., 48, RG2004, doi: 10.1029/2009RG000316.

Sawadogo, Y., Koala, S., Zerbo, JL., 2022, *Factors of geomagnetic storms during the solar cycles 23 and 24: A comparative statistical study*, Scientific Research and Essays, Vol. 17(3), pp. 46-56, DOI: 10.5897/SRE2022.6751

Yatini, C.Y., Suratno, Admiranto G., Suryana N., 2008. *Karakteristik Lontaran Massa Korona (CME) yang Menyebabkan Badai Geomagnet*, Jurnal Sains Dirgantara Vol.6, No.1