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# Solar cycle distribution of geomagnetic storms during solar cycle 21 to 24

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***Abstract:*** *The distribution properties of intense geomagnetic storms ($D_{st} \leq -100$ nT) and severe geomagnetic storms ($D_{st} \leq -200$ nT) over the solar cycles (21–24) are explored. The outcomes show that 68.5% of the intense geomagnetic storms occurred in the declining period of the solar cycles. 86.1% of severe geomagnetic storms happened in the declining period of the solar cycles. About 80% of the intense geomagnetic storms showed up during the period from the two years before solar cycle peak and the three years after solar cycle peak time. 89.5% of the severe geomagnetic storms showed up between the two years before solar cycle peak and the three years after solar cycle peak. At the point when a solar cycle is strong, the phenomenon that intense geomagnetic storms concentrated during the period from the two years before the solar cycle peak time to the three years after the solar cycle peak time is conspicuous. The dispatch time of space science satellite is recommended by the conveyance properties of intense geomagnetic storms and severe geomagnetic storms in solar cycles.*

***Key Words:*** *solar activity, geomagnetic storms, sun-earth connection.*

## 1. INTRODUCTION:

Intense geomagnetic storms ($D_{st} \leq -100$ nT) can be actuated by interplanetary coronal mass ejections (ICMEs) or a co-rotating interaction region (CIR) (Gosling et al. 1991; Tsurutani and Gonzalez 1997; Richardson et al. 2002; Zhang et al. 2007 and reference therein). Gonzalez et al. (1990) contemplated the double peak solar cycle conveyance of intense geomagnetic storms ($D_{st} \leq -100$ nT) happened during 1965–1985. The aftereffect of their paper gave proof that the appropriation of intense geomagnetic storms happened during a solar cycle has a two top with one peak happening at the late rising period of the solar cycle or at solar maximum and another at the early declining period of the solar cycle. The information gathered during the time of 1965–1985 (Gonzalez et al. 1990) is not long enough to produce the outcomes that are measurably significant. So as to check whether the double peak distribution of intense geomagnetic storms has the comparative conveyance, they picked aa index (Mayaud 1980) as an appropriate indicator of the geomagnetic activity and examined the solar cycle distribution of intense geomagnetic storms with aa index >100 nT happened during solar cycles (12–19). Be that as it may, aa index isn't $D_{st}$ index. The solar source of an intense geomagnetic storm can be a coronal hole or a coronal mass ejection (CME).

An intense geomagnetic storm ($D_{st} \leq -100$ nT) is a significant Sun-Earth association occasion during which the aggravation brought about by a CME propagated from the sun to the earth. Geomagnetic storms at this level may impose a very enormous effect on satellite attitude, navigation, and positioning, and henceforth is a significant player in arranging severe space weather occasions. In this context, intense geomagnetic storm is a key worry that must be tended to in space climate study and forecast. The solar sources for all intense geomagnetic storms happened during solar cycle 23 are CMEs (Zhang et al. 2007; Echer et al. 2008). Right now, dissemination of intense geomagnetic storms in solar cycles reflects the distribution of CME occasions that may lead the event of intense geomagnetic storms in a solar cycle, particularly with regards to timing and frequency of significant Sun-Earth association occasions.

An intense geomagnetic storm isn't only different from a severe geomagnetic storm in number, but at the same time is diverse in physical significance, during a solar cycle. An intense geomagnetic storm can either be originated from a CME, or from a coronal hole. Be that as it may, an intense geomagnetic storm must be sourced from a CME. As for as the timing of launching a satellite to probe significant sun-earth association occasions is concerned, the best window time is the one when most of intense geomagnetic storms have not yet happened in a solar cycle. Somewhere in the range of 50 years have slipped by since 1957, which makes a decent chance to contemplate the measurable conveyance of intense geomagnetic storms in solar cycles.

Gonzalez et al. (2011) explored the solar cycle distribution of outrageous storms. Their outcomes show that severe geomagnetic storms happened during all periods of the solar cycle, in spite of the fact that with a higher inclination around solar maximum and at the early descending period of the solar cycle. Their outcomes likewise show that there was a double peak distribution of severe geomagnetic storms. Echer et al. (2011) made a measurable report on the geomagnetic storms with peak Dst≤−50 nT from 1957 to 2008. The outcomes in their paper show that geomagnetic storms show a two-peak appropriation during a solar cycle, with one peak near solar maximum and the other a couple of years after the fact in the start of the declining phase. Neither one nor the other papers presented the percentages that storms happened in the inclining and descending periods of a solar cycle. A scope of different issues, remembering for what timeframe intense geomagnetic storms would generally happen when the solar cycle peak time, and would the solar cycles with various amplitude be contrasted in the incidences of intense geomagnetic storms, have not yet been managed.

We made a measurable examination of the incidences of intense geomagnetic storms in the rising and declining periods of a solar cycle, in view of the intense geomagnetic storms data gathered since 1957 and smoothed month to month mean sunspot numbers. From that point forward, we investigated in what time period intense geomagnetic storms would for the most part happen when the solar cycle peak time. At long last, the distributions of intense geomagnetic storms in solar cycles with various amplitude were analyzed. Based on statistical outcomes, a few proposals were advanced concerning the planning of propelling a satellite intended to test significant sun-earth occasions, which is likewise the motivation behind this paper.

## 2. Data analysis :

Table.1 lists the intense geomagnetic storms that happened during the time of 1976–2019 by solar cycle. Each solar cycle is given the month and year where an intense geomagnetic storm appeared, the day having the most minimal $D_{st}$ index, and the least $D_{st}$ index. Each solar cycle is additionally delineated with time reference, including the beginning, peak, and end of a solar cycle as smoothed month to month mean sunspot number (SMMSNs). The paper presents the phase distribution of intense geomagnetic storms in solar cycles beginning from 1957, a base year from which the World Data Center in Japan set out on $D_{st}$ information collection.

**Table 1** The intense geomagnetic storms occurred during 1976-2019.

**Solar cycle 21**

| Year | Intense | Severe | Total |
|---|---|---|---|
| 1976 | 34 | 9 | **43** |
| 1977 | 31 | ------ | **31** |
| 1978 | 117 | 8 | **125** |
| 1979 | 70 | 1 | **71** |
| 1980 | 28 | 6 | **34** |
| 1981 | 189 | 11 | **200** |
| 1982 | 197 | 32 | **229** |
| 1983 | 63 | 2 | **65** |
| 1984 | 31 | ------ | **31** |
| 1985 | 34 | ------ | **34** |
| 1986 | 73 | 7 | **80** |
| **Total** | **867** | **76** | **943** |

**Solar cycle 22**

| Year | Intense | Severe | Total |
|---|---|---|---|
| 1987 | 01 | ------ | **01** |
| 1988 | 73 | ------ | **73** |
| 1989 | 233 | 139 | **372** |
| 1990 | 131 | 9 | **140** |
| 1991 | 317 | 36 | **353** |
| 1992 | 193 | 12 | **205** |
| 1993 | 31 | ------ | **31** |
| 1994 | 44 | 02 | **46** |
| 1995 | 22 | ------ | **22** |
| 1996 | 02 | ------ | **02** |
| **Total** | **1047** | **198** | **1245** |

**Solar cycle 23**

| Year | Intense | Severe | Total |
|---|---|---|---|
| 1996 | 02 | ------ | **02** |

| | | | |
|---|---|---|---|
| 1997 | 18 | ------ | **18** |
| 1998 | 123 | 02 | **125** |
| 1999 | 51 | 04 | **55** |
| 2000 | 150 | 20 | **170** |
| 2001 | 194 | 45 | **239** |
| 2002 | 132 | ------ | **132** |
| 2003 | 78 | 32 | **110** |
| 2004 | 96 | 19 | **115** |
| 2005 | 49 | 3 | **52** |
| 2006 | 12 | ------ | **12** |
| 2007 | ------ | ------ | ----- |
| 2008 | ------ | ------ | ----- |
| **Total** | **1245** | **125** | **1015** |

**Solar cycle 24**

| Year | Intense | Severe | Total |
|---|---|---|---|
| 2009 | ------ | ------ | ------ |
| 2010 | ------ | ------ | ------ |
| 2011 | 15 | ------ | **15** |
| 2012 | 59 | ------ | **59** |
| 2013 | 14 | ------ | **14** |
| 2014 | 2 | ------ | **2** |
| 2015 | 62 | 3 | **62** |
| 2016 | 2 | ------ | **2** |
| 2017 | 10 | ------ | **10** |
| 2018 | 10 | ------ | **10** |
| 2019 | ------ | ------ | ------ |
| **Total** | **174** | **3** | **174** |

During the time of (1976-2019), 867 intense geomagnetic storms happened. Of them, 182 appeared in the rising period of the solar cycle 21, and 685 others in the inclining phase. Solar cycle 22 saw 1047 events of intense geomagnetic storms, with 74 in the inclining phase and 973 others in the descending phase. Solar cycle 23 enlisted 905 intense geomagnetic storms. 194 of them showed up in the inclining phase and 711 others in the declining phase. Solar cycle 24 saw 174 events of intense geomagnetic storms, with 88 in the inclining phase and the remaining 86 in the declining phase. During the time of (1976–2019), 2993 intense geomagnetic storms happened.

Of them, 538, or 17.9% of the aggregate, showed up in the rising period of solar cycles, and 2455, or 82.02%, in the declining period of solar cycles, proposing that most intense geomagnetic storms incline to appear in the declining period of solar cycles. During the time of 1976–2019, 402 severe geomagnetic storms ($D_{st} \leq -200$ nT) happened, with just 13 in the inclining phase, 378 others in the declining phase. During a similar timeframe, 5 super geomagnetic storms at the level of $D_{st} \leq -400$ nT happened, with 3 in the inclining phase and 2 others in the declining period of the solar cycle 22 and 4 super geomagnetic storms, with 2 in the rising phase and 2 in the declining phase.

The statistical numbers of the geomagnetic storms happened between the two years before the solar cycle peak time and the three years followed and their extent altogether were given in Table 2. One can see from Table 2 that 78.7% of the intense geomagnetic storms ($-200$ nT $< D_{st} \leq -100$ nT) happened between the two years before the solar cycle peak time and the three years followed, and 89.5% of the severe storms occurred in the period from the two years before the solar cycle peak time to the three years followed, which demonstrates that severe storms obviously preferred their outbreak during the period from the two years before the solar cycle peak to the three years followed.

To comprehend the connection between the adequacy of a solar cycle and the distribution properties of intense geomagnetic storms, we made a statistical investigation for the intense geomagnetic storms happened between the two years before each solar cycle peak time and the three years after the solar cycle peak time. The statistical outcomes were given in Table 3. It tends to be seen from Table 3 that 73.2%, 83.9%, 80.6% and 85.9% of the intense geomagnetic storms happened between the two years before the solar cycle peak time and the three years after the solar cycle peak time for solar cycles 21, 22, 23 and 24, respectively. Solar cycles 22 and 24 have higher amplitude than solar cycles 21 and 23. In any case, 73.2% and 80.6% of the intense geomagnetic storms happened between the two years before the solar cycle peak and the three years after the solar cycle peak time for the two solar cycles (21

and 23) having lower amplitude, recommending that the stronger the solar cycle is, the more the intense geomagnetic storms will happen in the two years before the solar cycle peak time and the three years followed.
The intense geomagnetic storms that happened during the time of 1976–2019 by solar cycle are appeared in Fig. 1. The severe geomagnetic storms that happened during the time of 1976–2019 by solar cycle are appeared in Fig. 2.

## 3. Summary and discussions :

The above mentioned investigation has led to the following conclusions:

1. During the time of 1976–2019, there were 2993 geomagnetic storms ($D_{st}$≤−100 nT). 538 storms, or 17.9% of the aggregate, occurred in the inclining period of solar cycles, and 2455 others, or 82.02%, in the declining phase. as far as the severe geomagnetic storms are concerned, 13 storms, or 3.0% of the aggregate, showed up in the inclining phase, and 378 others, or 94.02%, in the declining phase.

2. For the geomagnetic storms with a intensity of −200 nT < $D_{st}$ < −100 nT, the one happened during the period from the two years before the solar cycle peak time to the three years followed took up 78.7% of the total storms under this classification. At the level of −300 nT < $D_{st}$≤−200 nT, the one happened during the period from the two years before the solar cycle peak time to the three years followed represented 89.5% under the classification. This demonstrates intense geomagnetic storms or severe geomagnetic storms generally preferred their incidences in the two years before the solar cycle peak and in the three years followed. Of them, severe geomagnetic storms bested others.

**Table 2** The ratio of the geomagnetic storms occurred between the two years before solar cycle peak and the three years after solar cycle peak.

| Storm intensity | Dst ≤ -200 nT | | | |
|---|---|---|---|---|
| | -200 nT ≤ Dst ≤ -100 | Dst ≤ -200 nT | -200 nT ≤ Dst ≤ -100 | Dst ≤ -200 nT |
| **Numbers** | $N_{I(23)}$ | $N_{S(23)}$ | $N_{I(total)}$ | $N_{S(total)}$ |
| | 2357 | 360 | 2993 | 402 |
| **Total** | $N_{I(23)} + N_{S(23)}$ = 2357 + 360 = 2717 | | $N_{I(total)} + N_{S(total)}$ = 2993 + 402 = 3395 | |
| **Ratio (23)** | Ratio ($I_{23}$) = $N_{I(23)}$ /$N_{I(total)}$ = 2357/2993 =78.7% | | Ratio ($S_{23}$) = $N_{S(23)}$ /$N_{S(total)}$ = 360/402 =89.5% | |
| **Ratio (23t)** | $N_{I(23)} + N_{S(23)}$ / $N_{I(total)} + N_{S(total)}$ =2717/3395 =80.0% | | | |

$N_{I(23)}$ indicates the number of the geomagnetic storms at the level of −200 nT < $D_{st}$ ≤ −100 nT occurred between the two years before solar cycle peak and the three years after solar cycle peak, $N_{I(total)}$ indicates the total numbers for the geomagnetic storms with an intensity −200 nT < Dst ≤ −100 nT. $N_{s(23)}$ indicates the number of the geomagnetic storms at the level of Dst ≤ −200 nT occurred between the two years before solar cycle peak and the three years after solar cycle peak. $N_{s(total)}$ indicates the total numbers for the geomagnetic storms with an intensity $D_{st}$ ≤ −200 nT.

**Table 3** The statistical information for the great geomagnetic storms occurred during the period from the two years before solar cycle peak and the three years after solar cycle peak.

| Solar cycle | Sunspot number | Solar cycle length (year) | Dst ≤ -100 nT | | Ratio |
|---|---|---|---|---|---|
| | | | $N_{23}$ | $N_{total}$ | $N_{23}/N_{total}$ |
| 21 | 219.86 | 10.5 | 690 | 943 | 73.2 % |
| 22 | 211.21 | 9.9 | 1044 | 1245 | 83.9 % |
| 23 | 173.82 | 12.3 | 831 | 1030 | 80.6 % |
| 24 | 113.58 | 11.2 (active) | 152 | 177 | 85.9 % |

$N_{23}$ indicates the number of the intense geomagnetic storms at the level of $D_{st}$ lower or equal −100 nT occurred during the period from the two years before solar peak time three years after the solar peak time. $N_{total}$ is the total number of the intense geomagnetic storms occurred in a solar cycle.

3. The three solar cycles having higher amplitude (22, and 24) represented 83.9%, 85.9% respectively for the incidences of severe geomagnetic storms in the two years before the solar cycle's peak and in the three years followed. The two solar cycles having a weaker intensity (21 and 23) would sit at 73.2% and 80.6% respectively for the incidences of intense geomagnetic storms enlisted in the two years before the solar cycle peak time and in the three years followed, recommending that the stronger the solar cycle (22 and 24) is, the more the intense geomagnetic storms would happen in the two years before the solar cycle peak time and in the three years followed, and that in a

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weaker solar cycles (21, 23), a similar phenomenon would be less observable, as a significant number of intense geomagnetic storms would happen three years after the solar peak time.

Solar cycles 22 enrolled the event of 5 geomagnetic storms at the level of $D_{st} \leq -400$ nT, with 3 in the rising phase and 2 others in the declining phase and solar cycle 23 enlisted the event of 4 geomagnetic storms at the level of $D_{st} \leq -400$ nT, with 2 in the inclining phase and others in the declining phase. The one that appeared on 2:00 A.M March 14, 1989 makes the strongest geomagnetic storm at any point happened during solar cycles 21–24, with the least $D_{st}$ index at −589 nT, which makes the storm the just one having a $D_{st}$ index that is lower than −500 nT in the cycles.

At the point when a CME left the sun lastly arrived at the earth and afterward created intense geomagnetic storms, we consider it a significant Sun-Earth association occasion. The investigation made in the paper shows that most significant Sun-Earth association occasions occurred in the declining period of a solar cycle. Some severe geomagnetic storms have been seen close to sun solar minimum years. For instance, a severe geomagnetic storm with the base $D_{st}$ at −307 nT showed up in February 1986 (Wang et al. 1998). Right now, may expect intermittent events of severe geomagnetic storms even in a solar minimum year. It merits referencing that most intense geomagnetic storms would happen either inside the two years before the solar maximum year, or inside the three years after, however a severe geomagnetic storm might be seen close to a solar minimum year. Geomagnetic storms at the level of $D_{st} \leq -400$ nT additionally slope to turn up in the region of solar maximum year, with the biggest storm ($D_{st}$ = −589 nT) appearing before solar maximum year.

A geomagnetic storm is the consequence of solid communications between the solar output matters and the magnetosphere. The magnetic and plasma properties of ICMEs and the related sheaths, specifically the quality and span of the dawn-dusk solar wind electric field, controlled by the southward magnetic field component (Bs ), regulate the geo-adequacy of these structures (Akasofu 1981). Gonzalez et al. (1994) said that solar wind speed (V), south coordinated interplanetary magnetic field (Bs), and length of the Bs have greatest effect on causing geomagnetic storms. On the off chance that the sheath or the ICME has strong and long term southward magnetic field and enormous solar wind dynamic pressure, Dp then an intense geomagnetic storm will occur if such sort of solar wind structure arrives at the magnetosphere. Anyway, an intense geomagnetic storm is constantly activated up by a strong CME occasion. Right now, strong CME occasion is constantly connected with the outbreak of huge dynamic region. The statistical outcomes cited in the paper, therefore, reflect the way that when a solar cycle is strong, enormous activity regions would be seen for the most part in the two years before the solar cycle peak and in the three years followed. In a weaker solar cycle, an impressive number of enormous active regions would seem three years after the solar cycle peak time, in addition to their appearance in the two years before the solar cycle peak time and in the three years followed.

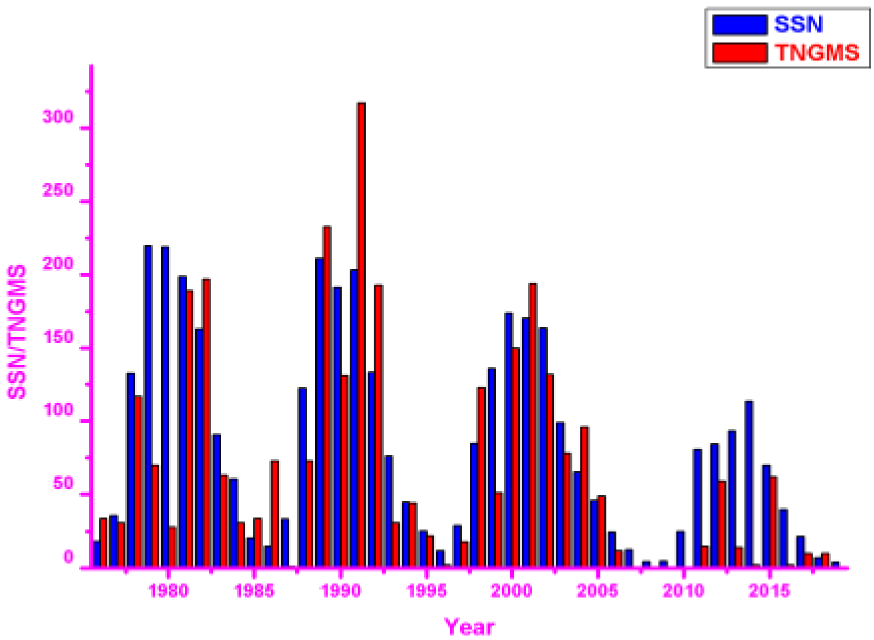


**Figure.1** Smoothed monthly mean sunspot numbers and number of intense geomagnetic storms during the period of 1976–2019.

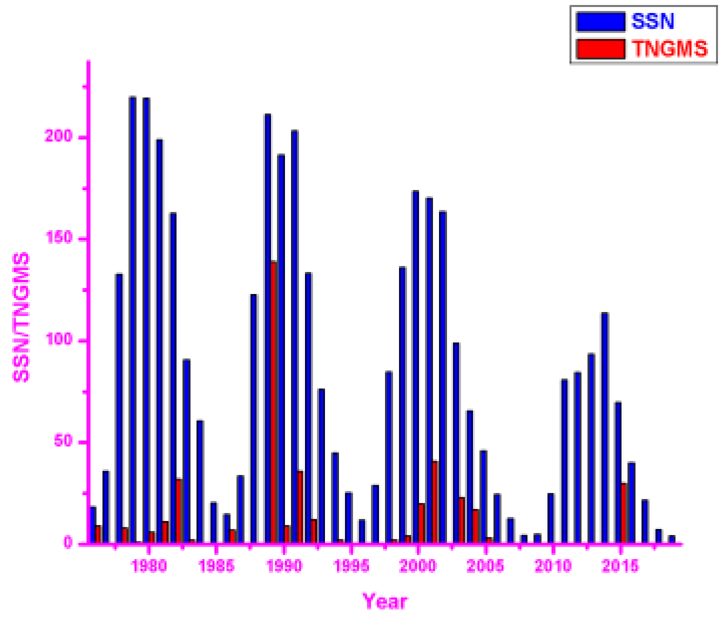


**Figure.2** Smoothed monthly mean sunspot numbers and number of severe geomagnetic storms during the period of 1976–2019.

Statistical outcomes got from the investigation are deductively edifying, as they can be utilized to characterize an ideal window of time for propelling space probe satellites. A space probe satellite must be launched under such a time period, that it is in a situation to contemplate significant solar terrestrial relations. The most attractive window of time for propelling a probe satellite is inside the two years before the solar maximum year of a solar cycle, permitting the probe to see practically all the significant Sun-Earth association occasions in a solar cycle.

As a compromise, one may dispatch a probe to see an important number of significant Sun-Earth association occasions in the solar maximum year of the solar cycle. Be that as it may, perception openings can be beyond a reasonable doubt bargained, if the probe is propelled in the three years after solar maximum year, specifically, the super storm occasions would be uncommon. The amplitude of solar cycle 24 is very low. In solar cycle 24 the measurable numbers of the geomagnetic storms happened between the two years before solar cycle peak time and the three years followed as referenced in table 3. The statistical outcomes cited in this paper that the significant Sun-Earth occasions in solar cycle 24 has been observed from 2011-2019. 2015 is the peak year in solar cycle 24.

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