A statistical study of the likelihood of a super geomagnetic storm occurring in a mild solar cycle

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Abstract: The activities of geomagnetic storms are generally controlled by solar activities. The current solar cycle (SC) 24 is found to be mild; compared to SCs 19–23, the storm occurrence and size derived by averaging the occurrence number andDst around the solar maximum are reduced by about 50–82% and 36–61%, respectively. We estimate separately, for SC 19 to 24, the repeat intervals between geomagnetic storms of specific Dst, based on fits of power-law and log-normal distributions to the storm data for each SC. Repeat intervals between super geomagnetic storms with Dst≤–250 nT are found to be 0.36–2.95 year(s) for SCs 19–23, but about 20 years based on the data for SC 24. We also estimate the repeat intervals between coronal mass ejections (CMEs) of specific speed (Vcme) since CMEs are known to be the main drivers of intense storms and the related statistics may provide information about the potential occurrence of super geomagnetic storms from the location of the Sun. Our analysis finds that a CME with Vcme≥1860 km/s may occur once per 3 and 5 months in SC 23 and 24, respectively. Based on a Vcme-Dst relationship, such a fast CME may cause a storm with Dst=–250 nT if arriving at the Earth. By comparing the observed geomagnetic storms to storms expected to be caused by CMEs, we derive the probability of CME caused storms, which is dependent on Vcme. For a CME faster than 1860 km/s, the probability of a CME caused storm with Dst=–250 nT is about 1/5 for SC 23 or 1/25 for SC 24. All of the above results suggest that the likelihood of the occurrence of super geomagnetic storms is significantly reduced in a mild SC.

Keywords: solar cycle; super geomagnetic storm; repeat interval

Citation: Zhuang, B., Wang, Y. M., Shen, C. L., and Liu, R. (2018). A statistical study of the likelihood of a super geomagnetic storm occurring in a mild solar cycle. Earth Planet. Phys., 2, 112–119. http://doi.org/10.26464/epp2018012

1. Introduction

Geomagnetic storms, which are disturbances in the magnetic field of the Earth’s magnetosphere (e.g., Gonzalez et al., 1994; Tsurutani et al., 1997; Echer et al., 2005), are one category of major space weather events. The size of a geomagnetic storm can be quantified by the corresponding magnetic activity index, e.g., Dst index, which is used to distinguish storms of varying severity, such as weak storms with −50 nT<Dst<−30 nT, moderate storms with −100 nT<Dst<−50 nT, and intense storms with Dst≤−100 nT (Gonzalez et al., 1994). Moreover, if a storm is with Dst<−250 nT, we call it a super storm, following Astafyeva et al. (2014). Several famous cases have demonstrated that super geomagnetic storms can have significant influence on high-technical systems of modern society, e.g., spacecraft, radio communication, power grid, etc. On 1989 March 14, a geomagnetic storm with Dst=−589 nT (Cliver and Crooker, 1993) struck power systems in Canada and U.S., causing a major power outage for 9 hours in the majority of the Quebec region (Molinski et al., 2000). The “Halloween” event on 2003 October 30 with Dst=−385 nT affected the power system infrastructure, the aviation industry, and satellite communications in Europe and North America (Kappenman, 2005). Tsurutani et al. (2003) reviewed the Carrington event, on 1859 September 1–2, which was the most intense magnetic storm in recorded history with Dst estimated to be −1760 nT, and concluded that storms of that extreme strength may occur again. The serious potential hazards of future super storms make it important that the probability of their occurrence be studied (e.g., Borovsky and Denton, 2006; Kataoka and Ngwira, 2016).

Silbergleit (1997) adopted a predictive method of Gumbel’s first asymptotic distribution to estimate the repeat interval between storms of specific size, and found that a storm with Dst≤−600 nT may occur once per 7 solar cycles (SCs). Tsubouchi and Omura (2007) obtained a repeat interval of about 60 years between storms of Dst≤−589 nT by using extreme value theory estimation. Yermolaev et al. (2013) analyzed the standard and integral distribution functions of magnetic storm minimal Dst index for the period 1963–2012, and found that the repeat intervals between
storms of $D_{st} < -500$, –1000, and –1500 nT, respectively, are approximately 24, 250 and 1500 years. Love et al. (2015) provided fitting results and corresponding uncertainties for power-law and log-normal distributions of observed storm $D_{st}$ minima for years 1957–2012, and Riley and Love (2017) extended the data analysis to early 2016. However, these studies did not include the storms in SC 24, or included them in combined statistics for SCs 19–24. SC 24 is found to be extremely mild, with storm activities at the lowest level since the 1930s (Gopalswamy, 2012; Richardson, 2013; Gopalswamy et al., 2014). Moreover, SC 25 is predicted to be similar in strength to SC 24 (Cameron et al., 2016; Deminov et al., 2016; Hathaway and Upton, 2016). Accordingly, we study separately the likelihood of occurrence of super geomagnetic storms in a mild SC, and compare results to those observed in previous SCs. In this paper, we will study the repeat intervals between super geomagnetic storms in different SCs. Furthermore, coronal mass ejections (CMEs) are known to be main drivers of intense storms (Gosling et al., 1991; Richardson et al., 2002; Echer et al., 2006; Gonzalez et al., 2007). In order to investigate the likelihood of occurrence of CME caused superstorms we therefore study CME statistics to broaden our view out to the Sun instead of limiting the study to information only at the location of the Earth.

In Section 2, we first compare the occurrence and $D_{st}$ minima of geomagnetic storms in SC 24 with those in SCs 19–23, and then estimate the repeat intervals between storms of specific $D_{st}$. In Section 3, we study the CMEs in SCs 23 and 24 so as to provide additional information about the occurrence of the potentially CME caused storms. We give the conclusions in Section 4.

2. The Super Geomagnetic Storm Repeat Intervals from Solar Cycle 19 to 24

The World Data Center for Geomagnetism provides geomagnetic storm data online at http://wdcwww.kugi.kyoto-u.ac.jp/index.html. We use the minimal $D_{st}$ index recorded in each day to represent the daily geomagnetic storm size from 1957 January 1 to 2017 December 31. We also download the daily total sunspot number (SSN) record in the same period from the Sunspot Index and Long-term Solar Observations at http://sidc.be/silso/datafiles. First, we show the correlations between the annual count ($C_s$) and annual $D_{st}$ minima of intense storms with the annually averaged SSN in Figure 1. The correlation coefficients of SSN versus $C_s$ and SSN versus $D_{st}$ are 0.79 and –0.71, respectively. We then display the evolutions of these parameters along SC in Figure 2, in which $C_s$ and $D_{st}$ are found to behave in a similar fashion to SSN. We derive an averaged value of SSN in a SC based on the SSN covering the solar maximum year as well as one year before and after that. However, since there exists a dual-peak storm SC distribution (Gonzalez et al., 1990, 2011; Echer et al., 2011; Le et al., 2013), the averaged $C_s$ and $D_{st}$ in a SC are instead calculated based on some chosen peak values around the solar maximum, shown by the thick blue lines and blue crosses in Figure 2, respectively. These averaged values are listed in Table 1, and used for comparison in

![Figure 1](https://example.com/f1.png)

**Figure 1.** Data points of SSN versus $C_s$ (red circle) and SSN versus $D_{st}$ (black diamond). The dashed lines indicate the linear fits.

![Figure 2](https://example.com/f2.png)

**Figure 2.** Top: Histogram of the annual count ($C_s$) of intense geomagnetic storms in SCs 19–24. Bottom: Profile of the annually averaged SSN (black) along with the annual $D_{st}$ minima (red). The period of every SC is indicated by the vertical dashed lines; the blue symbols indicate the chosen $C_s$ and $D_{st}$ peak values.

| SC | SSN | $C_s$ | $D_{st}$ (nT) |
|----|-----|------|--------------|
| 19 | 252 | 31   | –427         |
| 20 | 149 | 14   | –335         |
| 21 | 212 | 22   | –287         |
| 22 | 202 | 38   | –471         |
| 23 | 169 | 21   | –404         |
| 24 | 97  | 7    | –185         |

Note: We average SSN of 1958–1960 in SC 19, 1969–1971 in SC 20, 1980–1982 in SC 21, 1990–1992 in SC 22, 2001–2003 in SC 23, and 2013–2015 in SC 24, respectively.
different SCs by calculating the relative differences between those
in SC 24 and those in SC 19 to 23. Overall, comparing SC 24 with
SC 19 to 23, there is a decline in SSN of about 35–61%, and C and
\( D_{st} \) are reduced by about 50–82% and 36–61%, respectively.

Figure 3 shows the accumulative histograms of the storm daily \( D_{st} \)
minima from SC 19 to 24, in which the number of the data points
used to construct each bin is the sum of all the data points to the
right of itself; the bin size is 10 nT. We then use power-law and
log-normal distributions to fit the data points since both distribu-
tions can be used to fit storms in terms of frequency versus sever-
ity (Love, 2012; Love et al., 2015; Riley and Love, 2017). The equa-
tions of the power-law and log-normal distributions are given by
equations (1) and (2), respectively, where \( N \) is the bin number, and
\( C_1, \alpha, C_2, \mu \) and \( \sigma \) are the fitted parameters:

\[
N = C_1 |D_{st}|^{-\alpha},
\]

\[
N = C_2 \frac{e^{-\mu(D_{st})^2/2\sigma^2}}{|D_{st}|}.
\]

We fit the data points for \( D_{st} \leq -50, -100, \) or \(-250 \) nT, and adjust the
fitted parameters carefully to make the corresponding reduced
chi-square value (\( \chi^2 \)) close to 1, in which \( \chi^2 = 1 \) in principle indicates that the estimates best
match the observations. The fitted results of the power-law and
log-normal distributions are shown by the colored curves in

**Figure 3.** Plot of the accumulative histograms of the storm \( D_{st} \)
daily minima from SC 19 to 24. The green, blue and red curves indicate the fitted
results of the power-law distribution on the data points with \( D_{st} \leq -50, -100 \) and \(-250 \) nT, respectively, while the shadow shows the errors.

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Figure 3 and 4, respectively, and are listed in Table 2. Note that here we can’t fit the data points with \( D_{st} \leq -250 \) nT in SC 24, since the minimum \( D_{st} \) in this SC is about \(-223 \) nT, which corresponds to the so-called St. Patricks Day event on 2015 March 17 (Kataoka et al., 2015; Wood et al., 2016; Wang et al., 2016). There are several elements to understand in the figures and tables. In Figure 3 of the power-law fit, all the red curves (fitting starting at \( D_{st} = -250 \) nT) are beneath the green and blue curves (fitting starting at \( D_{st} = -50 \) and \(-100 \) nT, respectively), and the blue ones are beneath the green ones. In Figure 4 of the log-normal fit, most of the curves are similar to each other except those in Figure 4a. In Table 2, most of the \( \chi^2 \) derived by fitting both distributions to the data points with \( D_{st} \leq -250 \) nT are closest to 1 in SCs 19–23, and \( \chi^2 \) with \( D_{st} \leq -100 \) nT is closest to 1 in SC 24. Therefore, to evaluate the data points extended to a smaller \( D_{st} \), we adopt both of the power-law and log-normal distributions to fit the data points, which are started at \( D_{st} = -250 \) nT in SC 19 to 23 and at \( D_{st} = -100 \) nT in SC 24, respectively. Finally, we can estimate the repeat intervals between storms of \( D_{st} \leq -250, -400 \) and \(-600 \) nT, respectively, where the related interval number at a specific \( D_{st} \) is derived by dividing the length of each solar cycle by the corresponding accumulative number of storms in that cycle. The results are listed in Table 3, along with the errors derived by the errors of the fitted data points (shown by the shadow in Figure 3 and 4), which are calculated by the formal 1-sigma errors in each fitted parameter in the solar software (SSW) MPFIT.PRO. From Table 3, we find that storms in SCs 19, 22 and 23 have similar repeat interval numbers, but the numbers in SCs 22 and 23 are slightly larger than those in SC 19. In SCs 20 and 21, with slightly weaker geomagnetic storm activities (see in Table 1 and Figure 2), the estimated storm repeat intervals

\[
\begin{align*}
\text{Figure 4.} & \quad \text{Same as Figure 3 but with the fitted results of the log-normal distribution.}
\end{align*}
\]
Table 2. Table of fitted parameters and their corresponding reduced chi-square values for power-law and log-normal distributions of storms with $D_{st} \leq$ 50, –100, and –250 nT, from SC 19 to SC 24

| SC | $D_{st}$ | Power-law | Log-normal |
|----|---------|-----------|------------|
|    |         | Coef ($C_1, \alpha$) | $\chi^2$ | Coef ($C_2, \mu, \sigma$) | $\chi^2$ |
| –50 | (1.9 × 10^6, –2.01) | 16.11 | (14846, 0.32, 1.41) | 8.09 |
| 19  | (1.0 × 10^6, –2.41) | 6.35 | (10954, 0.57, 1.37) | 4.23 |
| –250 | (4.8 × 10^6, –4.73) | 1.18 | (5062, 2.95, 0.78) | 1.14 |
| –50 | (1.0 × 10^6, –2.55) | 8.19 | (11099, 1.16, 1.09) | 12.04 |
| 20  | (5.0 × 10^6, –2.89) | 2.56 | (5782, 1.36, 1.11) | 1.42 |
| –250 | (7.9 × 10^6, –4.70) | 1.31 | (3154, 1.98, 0.97) | 1.02 |
| –50 | (2.0 × 10^6, –2.61) | 6.34 | (12975, 1.14, 1.05) | 4.75 |
| 21  | (2.0 × 10^6, –3.11) | 2.73 | (25401, 0.80, 1.16) | 1.29 |
| –250 | (6.9 × 10^6, –4.03) | 1.45 | (9920, 1.61, 1.01) | 0.66 |
| –50 | (1.0 × 10^6, –2.39) | 7.72 | (3325, 2.45, 0.88) | 2.88 |
| 22  | (2.0 × 10^6, –3.05) | 1.66 | (6735, 1.86, 1.01) | 1.79 |
| –250 | (1.6 × 10^6, –4.65) | 1.19 | (6934, 2.08, 0.96) | 0.60 |
| –50 | (6.0 × 10^6, –2.34) | 7.26 | (14159, 0.86, 1.22) | 15.64 |
| 23  | (1.0 × 10^6, –2.45) | 5.39 | (8759, 0.70, 1.32) | 6.33 |
| –250 | (3.0 × 10^6, –4.68) | 1.19 | (7041, 2.59, 0.85) | 1.11 |
| –50 | (5.0 × 10^6, –3.12) | 9.45 | (3381, 1.93, 0.86) | 3.63 |
| 24  | (5.0 × 10^6, –4.63) | 1.05 | (6163, 1.62, 0.90) | 0.43 |

become approximately ten times those in SCs 19, 22 and 23. Based on data for the mild SC 24, the repeat intervals are much larger than those in the previous SCs, showing that a storm may occur once per 25.3 (19.0), 223 (209) and 1458 (2073) years with $D_{st} \leq$ 250, –400 and –600 nT according, respectively, to the power-law (log-normal) distribution fits.

3. The Potential Occurrence of Super Geomagnetic Storms Caused by CMEs

Since CMEs are main drivers of intense geomagnetic storms, the statistics of CMEs can provide additional information about the potential occurrence of super geomagnetic storms from the location of the Sun. The following analysis is based on data from the Large Angle and Spectrometric Coronagraph (LASCO, Brueckner et al., 1995) CME catalog at the Coordinated Data Analysis Workshop Data Center (CDAW, covering data until 2017 April 30; Yashiro et al., 2004; Gopalswamy et al., 2009). As mentioned by Wang and Colaninno (2014), small or faint CMEs could be detected in SC 24 rather than SC 23 because the LASCO image cadence nearly doubled after mid-2010. Therefore, we choose the CDAW/CMEs with speeds higher than 300 km/s and angular widths greater than 30°. Figure 5 shows the accumulative histograms, with bin size set to be 20 km/s, of the considered CMEs as a function of CME speed ($V_{CME}$) in SCs 23 and 24, and we directly estimate the repeat intervals between CMEs of a specific $V_{CME}$ from the histogram data points. In SC 23, the repeat intervals between CMEs of $V_{CME}$=1000, 1860 or 2500 km/s are found be 0.3 month, 3 months or 1.3 years, respectively. In SC 24, the corresponding values are 0.7 month, 5 months and 4.7 years.

We will study the likelihood of the occurrence of CME caused storms based on how large the $D_{st}$ would be if a storm was caused by a CME and the probability of a CME arriving at the Earth and causing a storm at that specific $D_{st}$. Several studies (e.g., Kane, 2005; Yue and Zong, 2011; Gopalswamy et al., 2014) suggested that $D_{st}$ is determined not only by $V_{CME}$ but also by the magnetic fields in the corona and interplanetary space. However, coronagraph observations do not include information about the magnetic fields. Some studies (e.g., Srivastava and Venkatakrishnan, 2002; Gopalswamy et al., 2008; Klicik et al., 2011) have shown a noteworthy $V_{CME}$–$D_{st}$ relationship, and thus we use equation (3), which was provided by Gopalswamy et al. (2008), to describe this relationship:

$$D_{st} = -0.1V_{CME} - 64 \text{ (nT).}$$

Equation (3) indicates that a CME with $V_{CME}$=1860 km/s may cause a geomagnetic storm with $D_{st}$=-250 nT if arriving at the Earth. We then derive the probability of a CME causing a storm at a specific $D_{st}$ in Figure 6. Figure 6a shows the accumulative histogram (blue) of the expected storms caused by CMEs based on the CME data points in SC 23 as a function of $D_{st}$ which is derived from equation (3), and the accumulative histogram (red) of the observed storms. The blue bin shares the same size as the red one. The ratio of the

Table 3. Estimated repeat intervals (in years) between geomagnetic storms of $D_{st} \leq$ 250, –400, and –600 nT

| SC  | –250 nT  | –400 nT  | –600 nT  |
|-----|----------|----------|----------|
|     | PL  | LN  | PL  | LN  | PL  | LN  |
| 19  | 0.36 (±0.06) | 0.37 (±0.04) | 3.31 (±0.48) | 3.27 (±0.47) | 22.8 (±3.4) | 29.2 (±4.8) |
| 20  | 2.68 (±0.78) | 2.95 (±0.77) | 27.3 (±8.4) | 19.6 (±5.9) | 204 (±66) | 122 (±30) |
| 21  | 1.82 (±0.46) | 1.91 (±0.45) | 16.0 (±4.3) | 13.1 (±3.5) | 106 (±29) | 83.3 (±24.3) |
| 22  | 0.89 (±0.16) | 0.96 (±0.23) | 7.62 (±1.35) | 6.37 (±1.73) | 48.8 (±8.9) | 39.8 (±9.1) |
| 23  | 0.66 (±0.09) | 0.68 (±0.14) | 5.92 (±0.92) | 5.48 (±1.26) | 39.8 (±6.3) | 42.7 (±11.2) |
| 24  | 25.3 (±3.7) | 19.0 (±3.0) | 223 (±32) | 209 (±35) | 1458 (±222) | 2073 (±361) |

Note: PL and LN indicate the power-law and log-normal distributions, respectively.
Figure 5. Plot of the accumulative histograms of CMEs as a function of $V_{\text{CME}}$ in SC 23 (left) and 24 (right), respectively. The dotted lines indicate that $V_{\text{CME}}=1000, 1860$ and $2500$ km/s, and the accumulative numbers at the corresponding speeds.

Figure 6. Accumulative histograms of the expected geomagnetic storms caused by CMEs (blue), as a function of $D_{st}$ and the observed geomagnetic storms (red) in SC 23 (a) and SC 24 (b), respectively. The vertical dotted lines indicate the values of $1/P$. In panel (b), the red solid (dashed) curve indicates the fitted data points by the power-law (log-normal) distribution.
red data points to the blue data points, $P$, gives the probability of a CME causing a storm. Note that here the location of the blue bin may not match perfectly with that of the red bin, so $P$ is calculated by dividing the red bin number by the number of the blue data point that is closest to the red one. $P$ is found to be about 1/35 at $V_{\text{CME}}=300$ km/s, but as high as 1/5 or 1/2 at $V_{\text{CME}}=1860$ or 2500 km/s, respectively. In Figure 6a, the blue line crosses the red line at $D_s=\approx320$ nT. It may be that equation (3) underestimates the $D_s$ of severe storms (refer to Figure 5a in Gopalswamy et al. (2008)), but it still makes sense to use equation (3) to compare relatively the likelihoods of occurrence of CME caused storms in different SCs. Similarly, we estimate $P$ in SC 24 in Figure 6b according to the corresponding CME data points and equation (3). Here we use the fitted data points of the power-law and log-normal distributions to represent the observed storms whose $D_s$ are smaller than $\approx223$ nT. $P$ is found to be about 1/110 at $V_{\text{CME}}=300$ km/s, and the power-law distribution fit gives $P=1/25$ at $V_{\text{CME}}=1860$ km/s and $P=1/12$ at $V_{\text{CME}}=2500$ km/s, respectively, while the other fit gives the related $P$ to be between 1/26 and 1/15. Overall, $P$ is found to be dependent on $V_{\text{CME}}$, and larger in SC 23 than in SC 24, which may indicate that the magnetic field strength determining the storm $D_s$ is a function of $P$.

4. Conclusions and Discussions
In this paper, we study the likelihood of the occurrence of super geomagnetic storms in a mild SC. First, we find that the storm occurrence and size, which are derived by averaging the annual occurrence number and annual $D_s$ minima of intense storms around the solar maximum, are reduced by about 50–82% and 36–61% in SC 24 compared to those in SCs 19 to 23, respectively. We then evaluate the repeat interval between super storms of specific $D_s$ by fits of power-law and log-normal distributions. We apply both fits to the storm data points with $D_{s_{\text{min}}}\leq50$, $-100$ or $-250$ nT in SC 19 to 23, and find that the fits starting at $D_{s_{\text{min}}}=-250$ nT give the most reliable results, as confirmed by minimum chi-square values. In SC 24, the results are based on the storm data points with $D_{s_{\text{min}}}\leq-100$ nT. This analysis finds that estimated repeat intervals of super geomagnetic storms in SC 24 are much larger than those in SCs 19–23, e.g., the fits of the power-law and log-normal distributions give the repeat interval between storms of $D_{s_{\text{min}}}\leq-250$ nT close to 20 years for SC 24 compared to less than 3 years for the previous 5 SCs. We also study the statistics of the CME occurrences in SCs 23 and 24. We find that a CME with $V_{\text{CME}}=1860$ km/s may occur once per 3 or 5 months in SC 23 and 24, respectively. According to a $V_{\text{CME}}-D_s$ relationship, such a fast CME may cause a storm with $D_{s_{\text{min}}}=-250$ nT if arriving at the Earth. By comparing the observed geomagnetic storms with the expected storms caused by CMEs, we derive the probability of a CME causing a storm, which is dependent on $V_{\text{CME}}$. For a CME faster than 1860 km/s, the probability of the CME causing a storm with $D_s$ less than $-250$ nT is 1/5 for SC 23 or around 1/25 for milder SC 24. All of the above results suggest that the likelihood of a super geomagnetic storm is significantly reduced in a mild SC. The upcoming SC 25, which is predicted to be as mild as SC 24, can be used to test these results.

Acknowledgments
We acknowledge and thank the World Data Center for Geomagnetism (Kyoto) for use of the geomagnetic storm $D_s$ database, and the Royal Observatory of Belgium (ROB) for use of sunspot number data. The CME catalog is generated and maintained at the CDAW Data Center by NASA and the Catholic University of America in cooperation with the National Research Laboratory. This work is supported by grants from NSFC (41774178, 41574165, 41421063, and 41274173), and the fundamental research funds for the central universities.

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