Extreme Space Weather Events

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\textit{Preparing for the Solar Maximum}

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Space Weather events are considered as High-impact, low-probability risks (HILP) events

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</thead>
<tbody>
<tr>
<td>Catastrophic (5)</td>
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<tr>
<td>Severe (4)</td>
<td></td>
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<td>Coastal flooding</td>
<td>Widespread electricity failure</td>
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<td>Moderate (3)</td>
<td>Major transport accidents</td>
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<td>Effusive volcanic eruption</td>
<td>Emerging infectious diseases</td>
<td>Inland flooding</td>
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<td>Minor (2)</td>
<td>Public disorder</td>
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<td>Animal diseases</td>
<td>Drought</td>
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<td>Limited (1)</td>
<td>Limited</td>
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Pandemic influenza

Severe space weather: Low temperatures and heavy snow, Heatwaves, Poor air quality events

May 08 - May 10: 4 X-class flares (X1.0-X2.2) before the storm came to Earth;
3 CME directed to Earth (source – Moon to Mars SW analysis office)
Aurora seen across unusual places; including Germany

Space weather impacts: Lot of effects have been reported but with limited impacts, including degradation of communication in HF range; some degradation of GPS services (e.g. reports from agricultural users); Starlink system degradation (unconfirmed), But no major impacts e.g. power outages, lost satellites etc.
Popular media and social networks demonstrated a surge of interest to space weather, and historical geomagnetic storms including Carrington event.

Comparison of sunspots for May 2024 storm (left) and spots group of Halloween events, superimposed with Carrington event spots.
How to Define Extreme Space Weather event?

Great geomagnetic storms can be defined by passing of some threshold value of Dst index e.g. -250 nT or based on some geophysical process associated with great geomagnetic storms, e.g., visible aurora latitude.

Japanese drawing showing auroral display at Okazaki (24.4 MLAT) during great storm of February 4, 1872. See Hayakawa et al., 2023 for the details.

Open circles – analytic fit to DMSP observations of auroral boundary (precipitating electrons) for all storms 1983 – 1991; color circles – historic events From Yokoyama et al., 1998; Cliver et al., 2022
Different Space Weather effects/impacts could occur at the same time due to close association with eruptive processes, but could also occur independently, e.g. radiation storms and geomagnetic storms. See Buzulukova and Tsurutani, 2022 for details.
Three major flares: the X17 on October 28; X10 on October 29, and X28-X34 on November 04; Corresponding estimated CME speeds are: 2125 km/sec, 1948 km/sec, 2300 km/sec The sunspot group seems to preserve its complexity and the most of energy after first 2 major flares (Credits: NOAA Service Assessment, 2004; Big Bear Solar Observatory)
Halloween Events of October – November 2003 (continued)

• >1 year after solar cycle passed the maximum (summer 2002);
• It was “calm before the storm”:
• 60 days before the outbreak: only 2 solar energetic events NOAA alerts;
• 3 weeks of end of October-November 2003: over 250 watches, warning, alerts
• 3 largest clusters of sunspots over last 10 years emerged;

Multiple impacts:
• Strong GICs over Northern Europe with system failures and blackouts;
• ISS astronauts were ordered to take a shelter;
• Airlines rerouted multiple flights with ~$10,000 - $100,000 per flight;
• GSFC reported that ~ 59% of Earth and Space Science missions were affected;
• ADEOS-2 s/c for ~$640 million was lost;
• Widespread concerns about affected commercial sectors generated intense media interest

Source: NOAA Service Assessment, 2004

Intense GICs and failures in the Swedish power transmission system. From Pulkkinen et al., 2005
Comparison of geomagnetic indices for Halloween events (10/29 – 10/31/2003) and great storm of 11/20-21/2003

For Halloween events, reported power outages happened during the main phase of storms or Sudden Storm Commitment (SSC) or auroral substorms during the main phase. No power outages were reported for November 2003 storm. Notably, different ICME speed (~2000 km/sec vs ~700 km/sec)
Recordings from the Kakioka Magnetic Observatory showing the first storm sudden commencement (SSC) starting at 01.27 UT and the second SSC starting at 07.43 UT on 13 March 1989. See Boteler, 2019 for the details.

Magnetic disturbances and effects on power systems during 13–14 March 1989 in North America and Europe. Horizontal bars indicate the times of power system effects. Black arrows indicate the times of the SSCs: Most of outages happened after 2nd SSC.
Interplanetary Sources for ‘intense’ geomagnetic storms

63% originated in ARs; 13% in quiet Sun regions: filaments or filament channels; 13% in CHs;
11% of CME-driven events showed no sign of eruptive features (no flare, no coronal dimming, no loop arcade, etc.)

Geomagnetic storm is defined from Dst index; strength of Dst depends on SW velocity (V) and southward component of IMF Bz (Bs)

Zhang et al., 2007 (black line – sunspot index)

Model 1 (O’Brien and McPherron, 2000):

\[
d \frac{d}{dt} Dst^* = Q(VB_z) - \frac{Dst^*}{\tau(VB_z)},
\]

\[
Q(VB_z) = \begin{cases} 
\alpha(VB_z - E_c) & VB_z > E_c, \\
0 & VB_z \leq E_c,
\end{cases}
\]

\[
\tau(VB_z) = \tau_\infty \exp \left( \frac{V_o}{V_q + VB_z} \right)
\]

Model 2:

\[ Dst_{min} = -0.01 \cdot V \cdot B_s - 32 \text{ nT} \]

(Gopalswamy, 2010)
Strongest observed flare (estimated X28-X34) during November 4th 2003
CME speed ~ 2000 km/sec but it missed the Earth... luckily...

Strongest recorded flare in history on November 4th

EIT 195 and LASCO Images for October 28 flare/CME (Credit: ESA/NASA)

GOES SXI and LASCO Images for November 4 flare/CME (Credit: NOAA/NASA)
Strongest recorded flare in history on November 4th (continued)

Re-defining GOES flare intensity with riometer data (D-region absorption). From Brodrick et al., 2005:

Riometers data: flare peaks 19:44–19:48 UT
NOAA estimations: ~ 19:50
NOAA detectors saturated for ~ 12 mins

NOAA estimations of flare intensity: X28
Corrections from riometers: X34
Sudden ionospheric disturbance - Solar Flare Effect – Magnetic Crochet as a measure of extreme flaring activity

Greenwich observatory magnetometer tracing for September 1, 1859 (top and bottom panels are shifted in time) From Cliver and Dietrich, 2013

Definition: A type of ionospheric disturbance associated with enhanced X-ray/EUV radiation from solar flares. This disturbance interferes with HF communication causing Radio Blackouts - important SW impact.

Delta t used to estimate CME speed

From Cliver and Svalgaard, 2004
Carrington event of September 2, 1859

1. Arguably, the most referenced ‘extreme space weather event’
2. Arguably, the most intense geomagnetic storm (currently under re-consideration)
3. White light flare; magnetic crochet
4. Striking effects of GICs: telegraph systems all over Europe and North America failed.

Estimations made by Tsurutani et al., 2003:
1) CME speed: ~ 2000 km/sec (comparable to Halloween event)
2) IMF ~ -100 nT
3) Dst ~-1600 nT
Estimations of Dst are currently being reconsidered most likely to be ~ - 800 nT

Number of citations of original Carrington work. From Cliver et al., 2022


Li et al., 2006

Green and Boardsen, 2006
Solar White Light Flares (WLF)s

- WLFs refers to visible continuum enhancement;
- At least 80% of the flares have WL continuum emissions, thus likely are WLFs (hard to detect);
- The most intense flares have clear white-light enhancement; including Carrington event (September 2, 1859)
- Majority of flare energy is in visible-UV range;
- GOES SXR energy is ~ 1% of the total energy;
- Wavelengths below 50 nm contribute between 10% and 20% ~ 70% of total flare energy can be estimated by using black body radiation with ~9000 K See Kretzschmar, 2011 for the details

Why important:
Visible WLFs likely present the most extreme conditions in solar flares (e.g., Carrington event);
WLFs are closely connected to WLFs on solar-like stars, superflares

Flare light curves averaged over 2100 flares (from X17.2 to C4) in various spectral ranges. From Kretschmar, 2011
Statistics of solar flares occurrence and power law for extreme flares

1-per-100 yrs flare: X42-X44; bolometric E ~ 4x10^{32} erg; 1-per-1000 yrs flare: X101-X115; bolometric E~10^{33} erg (There are empirical relations between NOAA XSR flux and flare bolometric energy). From Gopalswamy, 2018

CSHKP model for eruptive solar flares (Carmichael 1964; Sturrock 1968; Hirayama 1974; Kopp and Pneuman 1976; Hudson 2021)

The chart showing how the magnetic energy (bottom row) is distributed for an eruptive X-class flare. Estimations are done for 6 major flares averaging to X5.8. For the details see Cliver et al., 2022.
(A) Typical example of Kepler observations of a superflare on a solar type star. (B) An artist’s conception of a superflare and big starspots on a solar-type star based on Kepler observations. Right image is by courtesy of H. Magara. Bolometric $E$ for the flare from (A) is estimated to be $\sim 1.035 \text{ erg}$, $\times 200$ more than the biggest solar flare ($\sim 5.032 \text{ erg}$). See Cliver et al., 2022 for the details.
Observations by Kepler and TESS provide unique opportunity to expand statistics of solar flares and get better understanding of extremes for our Sun, and to understand the origin of life in the Universe.

Combined frequency distribution of Sun-like starts flares (slowly rotating Prot = 20-40 days), Teff =5000-6000K and solar flares. From Cliver et al., 2022

Scaling of flare bolometric energy to GOES XSR
See Cliver et al., 2022 for the details
Statistics of CMEs and power law for extreme CMEs

Cumulative distribution of CME speeds (left) and kinetic energies (right) from SOHO/LASCO catalog (https://cdaw.gsfc.nasa.gov) for the period 1996-2016. Power-law (e.g., Clauset et al. 2009) and Weibull (Weibull 1951) fits to the data points are shown. The 10 November 2004 CME at 02:26 UT has the highest speed of 3387 km/s. From Gopalswamy 2018.
Cumulative distribution of the omnidirectional SEP fluence in the >10 MeV (a) and >30 MeV (b) ranges. Weibull and power-law fits are shown on the plots. The 14 July 2000 SEP event had the highest fluence of $1.65 \times 10^{10}$ cm$^{-2}$ (>10 MeV) and $4.31 \times 10^{9}$ cm$^{-2}$ (>30 MeV). All fluences were computed from time profiles of NOAA’s GOES data. From Gopalswamy 2018.
Assuming the 774–775 AD event was caused by single SEP event, flare bolometric energy would be $0.5 - 3 \times 10^{35}$ erg!.. (comparable with famous 1956 GLE event scaled by factor $\sim 45$) Currently this is considered to be a very conservative estimation... (the most energetic solar flare so far is $5 \times 10^{32}$ erg) See Cliver et al., 2022 for the details.

Baseline adjusted radiocarbon response $^{14}$C in different trees around the year 774–775 AD as denoted in the legend: PL—Poland (Rakowski et al. 2015), YA—Yamal peninsula, Russia (Jull et al. 2014), GE—Germany (Usoskin et al. 2013), AL—Altai, Russia (Buntgen et al. 2018), JP—Japan (Miyake et al. 2012), CA1 and CA2—two sites in California, USA (Jull et al. 2014; Park et al. 2017), NZ—New Zealand (Guttler et al. 2015). The gray curve represents the model response to an instant production of 14C by a SEP event with a hard spectrum (Usoskin et al. 2013) taking place in mid-774 AD. Adapted from Uusitalo et al. (2018). See Cliver et al., for the details.
Statistics of extreme geomagnetic storms

Complementary cumulatives of $-\text{Dst}_1$ and $-\text{Dst}_2$ data, and their corresponding fitted models. Kolmogorov-Smirnov P-values are shown and model estimations of an event with $-\text{Dst}_1/-\text{Dst}_2$ that will exceed some threshold (per solar cycle). See Love, 2021 for the details.

Dst 1: 1st in intensity per solar cycle; Dst 2: 2nd in intensity per solar cycle
Definition of ‘extreme space weather event’ indeed depends on a particular parameter you are looking for. Example: extreme fluxes of outer radiation belt electron fluxes during geomagnetic storm(s) of July 2004.

A complex compound case: 3 ICMEs are followed by HSS. According to Katoka and Miyoshi, 2008, the explanation is related to lower dynamic pressure and expansion of magnetosphere thus removing magnetopause losses. (Other mechanisms for rad belt intensification include acceleration after strong interplanetary shock and acceleration during HSS/CIR storms)

For the details see Katoka and Miyoshi, 2008

Table 1. List of Top 10 Extreme Flux Enhancement

<table>
<thead>
<tr>
<th>Ranking</th>
<th>Max. Flux</th>
<th>Year</th>
<th>Month</th>
<th>Day</th>
<th>Total Day</th>
<th>Pd &lt; 1.0 nPa</th>
<th>Rec. Phase</th>
<th>CHS</th>
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<tr>
<td>1</td>
<td>5.223</td>
<td>2004</td>
<td>7</td>
<td>29</td>
<td>211</td>
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<tr>
<td>2</td>
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<td>2005</td>
<td>5</td>
<td>18</td>
<td>138</td>
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<tr>
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<td>9</td>
<td>19</td>
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<tr>
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<tr>
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<tr>
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<td>20</td>
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<td>4.590</td>
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<td>9</td>
<td>5</td>
<td>248</td>
<td>yes</td>
<td>not clear</td>
<td>yes</td>
</tr>
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*aThe data source is >2.0 MeV electron flux observed by GOES 8 or GOES 12 satellites during solar cycle 23. The time period from May 2003 to August 2003 is not included due to the observation data gap. The maximum flux is in unit of log 10 (/cm² sec str).
Ionosphere and neutral atmosphere response to an extreme event

- The response to truly extreme event at the Carrington-level has never been observed
- Have to rely on a physical model to estimate the likely response of the neutral and plasma density and the impact on satellite drag and communications and navigation systems
- Simulations performed using the WAM-IPE whole atmosphere model coupled to an ionosphere-plasmasphere-electrodynamic component
- Rationale: Make sure we have all the significant physical processes in the model. Simulate gradually increasing storm magnitudes from past intervals that have been observed. Make sure the physical model can reproduce the main features in the past observed responses. Scale up the biggest of the storms to simulate a Carrington-level event.
- A Carrington-level event with a Dst of ~-800 nT was estimated to be double the power, or twice the energy injected into the upper atmosphere as the Nov 2003 storm with a Dst of -472

Number of space objects that were lost of track of orbital motion after the great storm of March 13, 1989 due to unpredictable changes of orbits related to neutral density fluctuations

From Hapgood, 2018b
Neutral density

- A good match between WAM-IPE and observed neutral density data through storm periods with vastly different intensities, ten-times difference in storm response
- The good agreement between model and observations over the range of storm magnitudes enables the physical model to be used to estimate the response to a Carrington-level event with double the power of the Nov 2003 storm.
Neutral Density Response to a Carrington Event

Solar Wind velocity $\times 1.5$, IMF $B_z \times 1.5$

Magnetospheric forcing product $SW_{vel} \times B_z$ a factor of 2.25

Magnetosphere saturation decreases forcing to about a factor 1.8 to 2

Doubles the neutral density response at 400 km altitude compared to Nov 2003 storm. 8 to 10 times increase from quiet conditions.

Global mean peak density $> 800\%$

Max and Min Profiles at Peak

Carrington level
Nov 2003 level

- **Observations, modeling** focused on major new discoveries, key science questions & impacts
- **Citizen Science**
  - **Predictions & Reports**
  - **NOAA SWPC Solar Storm Warnings**
  - **NASA Moon2Mars Planetary Space Weather**
- **Data Commons**
  - **Model Output Commons**
- **Living Open Science Commons**
  - **Storm Narratives**
  - **Data Subset in AWS "Registry of Open Data"**
- **Modeling programs worldwide**
- **Models**
- **Scientific Satellites**
- **Evolving Space Environment**
- **HBY-SM Hub to identify leverage & highlight worldwide organic efforts.**
- **Layers from public outreach to Heliophysics researchers**
- **Queries about Heliophysics & Space Weather for both public & interdisciplinary communication**
- **Aim is to eventually use Natural Language Processing**
- **Exciting New Tools and Visualization Capabilities for HBY-SM**
- **Komodo - 3D model output and boundaries**
- **ISWA historical Open Space**
- **New Tools HDRL 3D Orbit Plotter**
- **Student HelioViewer**
- **Crowdsourcing app to add metadata on UT, location, star map overlay, etc. automatically on auroral photos**
- **Working toward stitching together photos to create global auroral image**
- **Innovative New Citizen Science Data Products**
- **Important Public-Facing Campaign Outcomes**
- **Preparing for the Solar Maximum:** [www.nasa.gov/sun/helio-big-year/](http://www.nasa.gov/sun/helio-big-year/)  
Some compelling science topics posed by storms during approach to Solar Cycle Maximum 25

Extreme Storms (min Dst)
- 23-24 Mar 2023 (-170 nT)
- 23-24 April 2023 (-178, -233 nT)
- 5-6 Nov 2023 (-189 nT)
- 10-11 May 2024 (-412 nT)

Mars SEP Event
- 20 May 2024

New Insights into the sources of Great Red Auroras, STEVEs, SAR-Arcs
- Great Red Aurora viewed from New Caledonia (-26.4°) & Puerto Rico (+27.2° MLAT)
- Red aurora observed from unusually low MLATs (i.e., CA, NM, NC, and FL)
- Red auroras observed in Europe that lasted only 5-15 min before fading in association with narrow peaks in storm intensity.
- Visible SAR Arcs
- STEVEs observed; SAR-arc transitioning to a STEVE (or being replaced by one).

Effects of exceptionally strong electric fields penetrating into mid-to-equatorial latitudes
- GOLD observations show equatorial ionization crest (EIA) merged with the southern auroral zone – Never seen before. Implies a powerful electric field & major reconfiguration of the ionosphere. [Karan et al., submitted, 2024b]
- GOLD shows northern EIA moved poleward to 35° MLAT; plasma bubbles reached 4000 km altitude. [Karan et al., submitted, 2024a] Unusually strong mid-to-equatorial electric fields driven simultaneously by multi-storm-time mechanisms—Not explainable by present models [Fejer et al., 2024]
- Strong electric field penetration to low latitudes as a result of sharp decrease in solar wind Pdyn. [Le et al., GRL, 2024] https://doi.org/10.1029/2024GL109427

Low Mach solar wind (Burkholder et al., GRL, 2024; Chen et al., 2024, arXiv:2402.08091)
- Interacting with sub-Alfvenic solar wind, bow shock disappears, magnetosphere exposed directly to the cold unshocked CME plasma & strong magnetic field. Magnetosphere transforms from windsock shape to having wings connected to Sun

Solar Sources of Extreme Activity
- 6 CMEs were hurled toward Earth by giant sunspot AR3664. Question arises did they interact to greatly enhance geoeffectiveness in producing a superstorm

Major SEP Event at Mars on 20 May 2024 caused by the same AR as but ½ solar rotation later
- Order of magnitude larger than any previously observed Mars’ GLE events. [A.Posner]
  What causes these events & what processes accelerate them?
This is not the end... Stay tuned for big surprises from Solar Cycle 25th!

Thank you!
References


https://doi.org/10.1007/s11207-005-4980-z


