

Geomagnetic Storm Research Based on Recent Geomagnetic Explosion

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Abstract

Geomagnetic storms, caused by disturbances in Earth's magnetosphere, have garnered significant attention due to their potential impact on technology and infrastructure. This article examines the origins and characteristics of geomagnetic storms, often triggered by solar activity like coronal mass ejections. The disturbance of Earth's magnetic field during these storms can lead to stunning auroras but also pose risks to satellite operations, power grids, and communication systems. Understanding these storms is crucial for developing strategies to mitigate their effects and protect vital technological systems on Earth.

Keywords: Geomagnetic storm, Earth's magnetic field, Geomagnetic Index

1. Introduction

Geomagnetic storms are severe disturbances in the global magnetic field of the Earth. Figure 1 is the overview diagram of the geomagnetic explosions. Use the geomagnetic index to indicate the size of land acquisition magnetic storms. Geomagnetic storms are the most representative global environmental disturbance events triggered by high-speed plasma clouds reaching Earth's space. The intensity of geomagnetic storms can characterize the magnitude of the impact of high-speed plasma clouds in solar storms. The intensity level of geomagnetic storms is generally divided into two types of geomagnetic indices: Kp index and Dst index. In research, Dst index grading is commonly used, while Kp index is used in early warning applications[1]. According to the National Space Weather Monitoring and Warning Center, a small to moderate geomagnetic storm may occur on December 4, 2023, due to the combined effects of the high-speed solar wind in the coronal cavity and the December 1 Coronal Mass Ejection (CME) from the Sun.

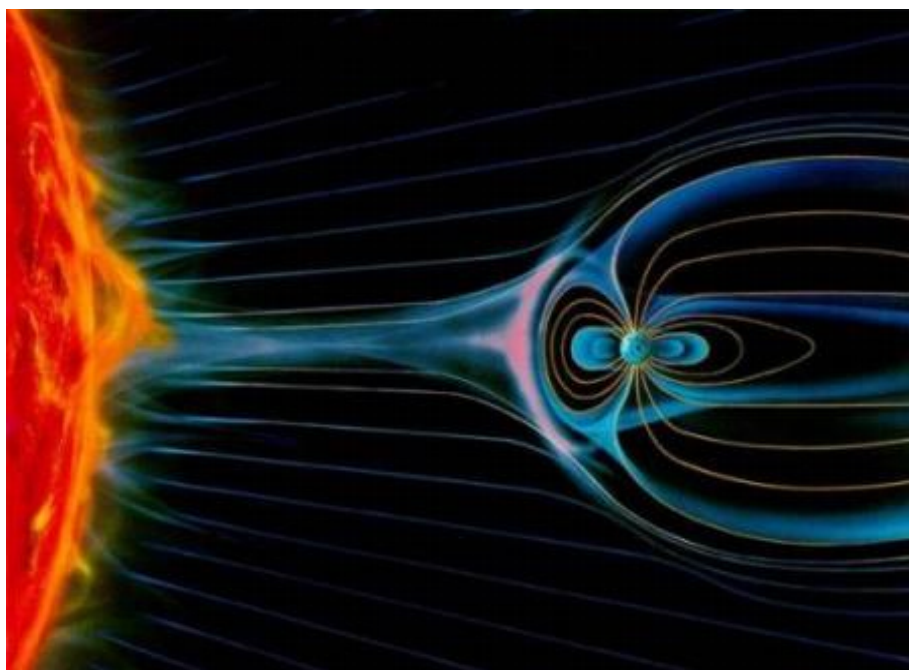


Figure 1. Overview diagram of geomagnetic explosions.[2]

2. Discovery of Geomagnetic Storms

In the 1830s, when German scientists Gauss and Weber established geomagnetic stations, they discovered that the geomagnetic field often had small fluctuations, but at that time they did not realize that this was caused by the sun. Later, on September 1, 1859, the British man Carrington was the first to observe a solar flare while observing sunspots. The next day, the geomagnetic station recorded a strong geomagnetic disturbance of 1600 nanometers. This accidental discovery and coincidence made him realize that geomagnetic disturbances were actually related to solar eruptions.

3. Cause of Geomagnetic Storms

A high-speed plasma cloud is ejected from the Sun's corona, with a higher relative velocity to the background solar wind. It carries the coronal magnetic field and impacts the Earth's magnetosphere, causing it to compress and deform. And it usually carries a magnetic field that rotates in the north-south direction. When the magnetic field turns south and interacts with the geomagnetic field, the solar wind will pour huge energy into the large-scale space of the magnetic tail, injecting a large number of charged particles in the plasma sheet of the magnetic tail into the ring current, causing a change in the strength of the ring current. The changing current will generate a changing magnetic field, causing severe geomagnetic disturbances on a global scale - geomagnetic storms.

There are two types of sources that can generate high-speed solar winds and trigger strong southward components of the interplanetary magnetic field: coronal mass ejections (CMEs) and coronal holes (as shown in Figure 2).

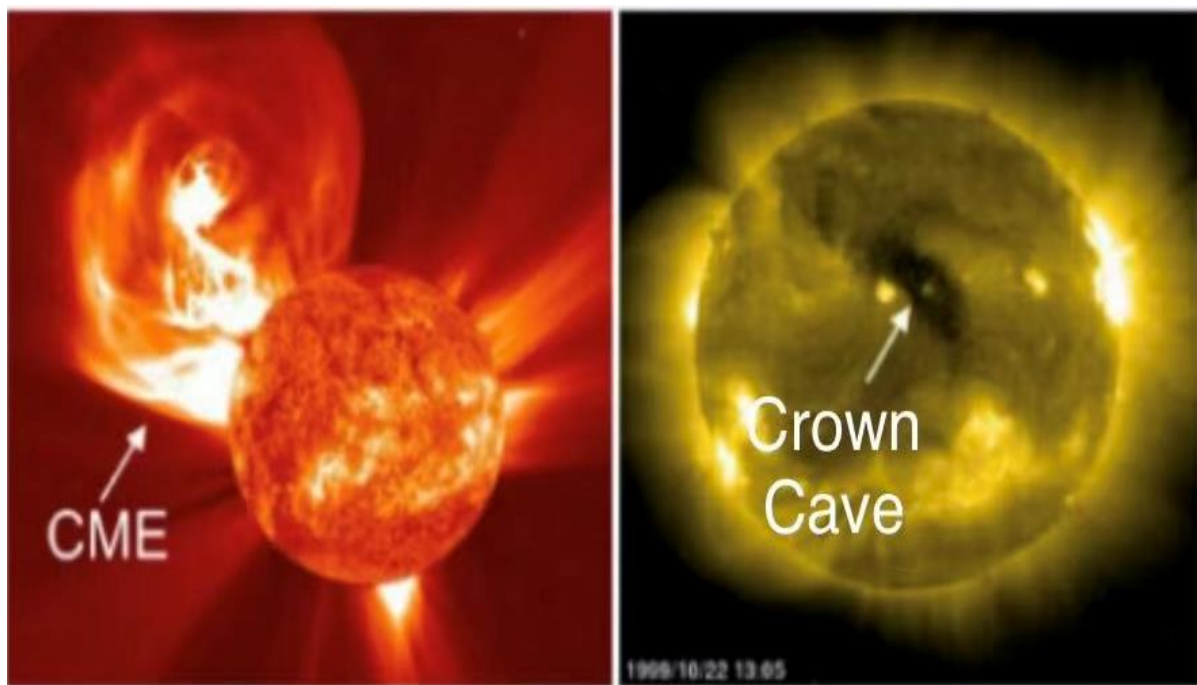


Figure 2. CME and Crown Cave.[3]

4. The Developing Process

When a geomagnetic storm occurs, this global and severe disturbance lasts for more than ten to dozens of hours throughout the entire magnetosphere, causing significant changes in all geomagnetic elements. The changes in the magnetosphere are shown in Figure 3. Among them, the geomagnetic horizontal component H has the largest variation, with disturbance amplitudes typically ranging from tens of nanometers to hundreds of nanometers, which best represents the characteristics of the magnetic storm process (its variation is most prominent in mid to low latitude areas). Therefore, most of the morphological and statistical characteristics of magnetic storms are obtained based on the variation of the mid to low latitude H component. The development process of typical magnetic storms is also divided into three stages based on the changes in the H component: initial phase, main phase, and recovery phase.

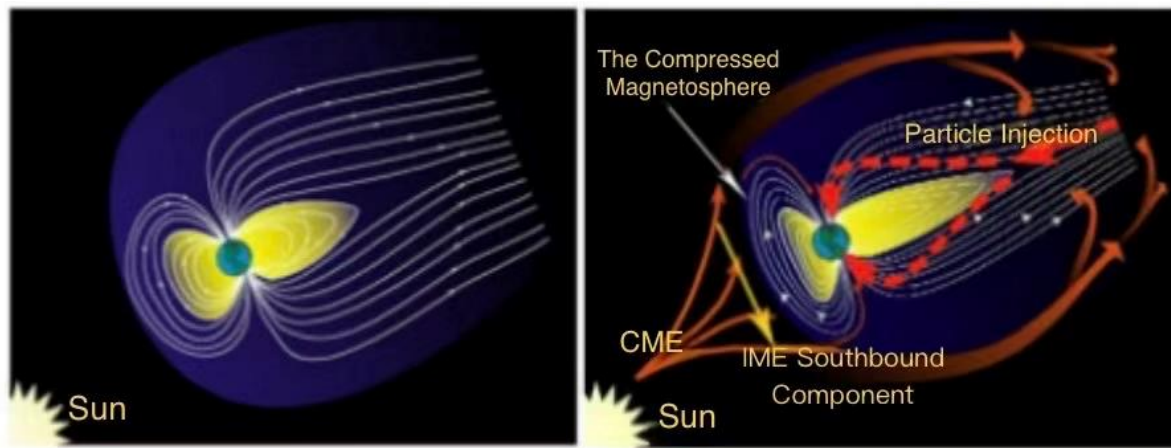


Figure 3. Changes in the magnetosphere before and after a magnetic storm.[3]

4.1 Initial Phase

After the start of a geomagnetic storm, the geomagnetic horizontal component fluctuates at levels higher than the pre storm value at various longitudes around the world, lasting for several tens of minutes to several hours. This stage is called the "initial phase".

4.2 Main Phase

After the initial phase ends, the H component suddenly decreases and reaches its minimum value within half an hour to several hours, which is called the "main phase". The main characteristic of a magnetic storm is the main phase, and the size of the storm is measured by the amplitude of the lowest point of the H-component decrease in the main phase stage. Generally, the H-component of a magnetic storm decreases by tens to hundreds of nanometers, and some large storms can exceed 1000 nanometers.

4.3 Recovery Phase

After the main phase, the H component gradually recovers to the level before the storm. During this period, the magnetic field still experiences fluctuations, but the overall disturbance intensity gradually weakens. It usually takes 2-3 days to fully recover to a calm state. This stage is called the "recovery phase". And Figure 4 shows the typical process of magnetic storm occurrence.

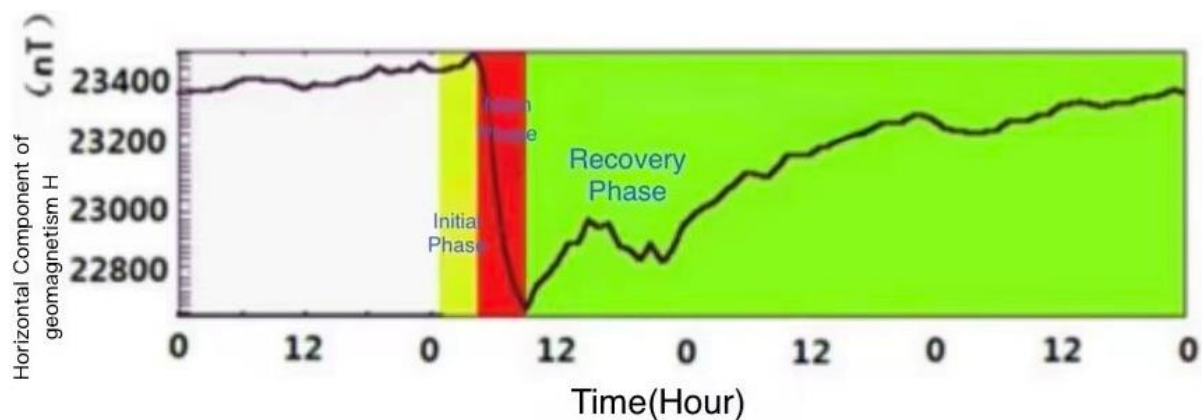


Figure 4. Typical process of magnetic storm occurrence.[3]

5. Geomagnetic Index

In summary, the geomagnetic index is a grading index based on geomagnetic monitoring data that describes the overall intensity of magnetic disturbances in a certain period of time or a certain type of magnetic disturbance intensity. It is based on basic theories and practical application needs, based on the actual measurement data of a station or a global station, using convenient and easy classification and simple and clear indicators, to review the

overall characteristics and describe the overall form of geomagnetic activity, and grasp the global or regional changes in the geomagnetic field from a macro perspective.

The geomagnetic activity index can be divided into two categories based on physical significance: the first category describes the overall level of geomagnetic activity, without considering the specific types of geomagnetic disturbances, among which the K index, Kp index, and Ap index are widely used; The second type is an index designed to describe specific types of magnetic disturbances or specific regions of magnetic disturbances, with the Dst index being widely used.

5.1 k-index

The "Three Hour Magnetic Situation Index" is an index that describes the intensity of magnetic disturbances within a single geomagnetic station during a 3-hour period. There are 10 levels from 0 to 9, where 0 represents calm geomagnetic activity and 9 represents the maximum amplitude of geomagnetic disturbance.

5.2 Kp index

The K index calculated from 13 geomagnetic stations in the global geomagnetic network is used to represent global geomagnetic activity, with a value every 3 hours ranging from 0 to 9, divided into 28 levels: 00, 0+, 1-, 10, 1+,..., 9-, 90. The gradual increase in its value indicates that the geomagnetic disturbance is gradually strengthening. In daily applications, Kp=5 and 6 are generally referred to as small and medium-sized geomagnetic storms, and Kp=7, 8, and 9 are referred to as geomagnetic storms.

The Kp index is not linearly related to the amplitude of magnetic disturbance, but approximates a logarithmic relationship. In order to represent the amplitude of magnetic disturbance changes, a global "three hour equivalent amplitude" ap index was defined based on the Kp index, with a unit of 2 nanometers Tesla. The average of 8 AP indices per day can be used as a measure of the global magnetic activity level, known as the Ap index. Figure 5 shows the changes in Kp index before and after magnetic storms. The Ap index ranges from 0 to 400, and the larger its value, the greater the amplitude of geomagnetic disturbance.

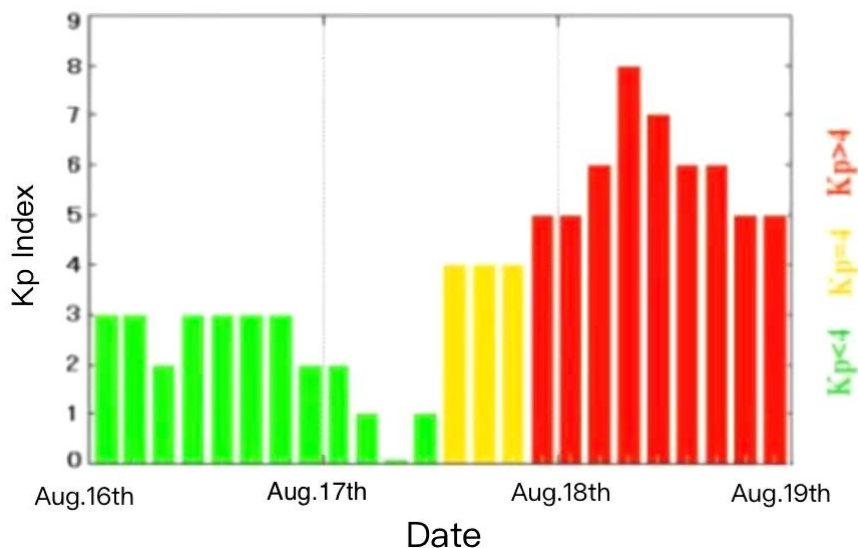


Figure 5. Changes in Kp index before and after magnetic storms.[4]

5.3 Dst Index

(Magnetic Storm Loop Current Index) Near the Earth's equator, four geomagnetic stations are selected at roughly uniform longitude intervals, and the average hourly variation in geomagnetic horizontal intensity at these four stations is the Dst index. Its unit is nanometers, and its range can range from positive tens of nanometers to negative thousands of nanometers, with a gradually decreasing value indicating an increasing magnetic disturbance amplitude.

6. Hazards and Impacts

During geomagnetic storms, processes such as high-energy particle deposition and Joule heating cause the lower atmosphere to expand and heat up, resulting in an increase in the density of the upper atmosphere; Changes in the density, composition, and wind field of the upper atmosphere can cause ionospheric storms; When the

magnetosphere is severely disturbed, the hot plasma in the magnetotail is accelerated to move towards the Earth, forming a hot plasma injection; Charged particles settle along magnetic field lines, bombarding the upper atmosphere and forming colorful auroras; During magnetospheric disturbances, electrons in the magnetosphere may be accelerated to high energy, causing a global phenomenon of high-energy electron enhancement - high-energy electron bursts.

6.1 Impact on Satellites

6.1.1 Direct Influence

When the local magnetic field is disturbed, changes in the direction and magnitude of the magnetic field can affect the torque between them, leading to changes in the satellite's attitude. After the attitude of the satellite changes, communication satellites will be unable to communicate normally, and sometimes may even interrupt communication; Meteorological satellites and military satellites are also unable to monitor the Earth.

6.1.2 Indirect Impact

When a strong magnetic storm occurs, the top of the magnetosphere is compressed into the geostationary orbit due to the intense compression of the high-speed solar wind, resulting in a crossing event of the magnetopause in the geostationary orbit. At this point, not only will the attitude be affected by changes in the magnetic field environment, but it will also be directly impacted by the solar wind due to the loss of magnetic field protection.

When a local magnetic storm occurs, Joule heating and auroral particle deposition heating cause global warming of the upper atmosphere, resulting in changes in density and composition. When the atmospheric density suddenly increases, the atmospheric resistance will suddenly increase, accelerating the speed of spacecraft attenuation, causing it to deviate from the expected path and even fall into the lower atmosphere and fall prematurely.

6.1.3 Case

1. During Halloween in 2003, the sun experienced a strong magnetic storm (geomagnetic storm), causing varying degrees of damage to a series of scientific satellites in Europe and America, leading to interference in global satellite communication.

2. On February 4, 2022, due to solar activity causing a geomagnetic storm, the Earth's upper atmosphere was heated and expanded, resulting in an increase in the density of the upper atmosphere. A group of star chain satellites experienced a significant increase in atmospheric resistance in their 210 kilometer orbit, a 50% increase in resistance compared to before the geomagnetic storm. In the end, 40 of these 49 satellites were unable to exit safe mode and activate krypton ion thrusters. According to SpaceX's announcement, only 9 of these 49 satellite chains are working properly. The American space exploration technology company stated that due to a geomagnetic storm, up to 40 of the 49 Starlink satellites launched by the company on February 3, 2022 were damaged the next day. It is believed that this is the largest scale damage caused to satellites by a single geomagnetic storm.

6.2 Impact on the Power Grid

During a strong magnetic storm, the geomagnetic field undergoes drastic disturbances and changes. The changing geomagnetic field generates Earth Surface Potential (ESP) in areas with high soil resistivity, ranging from a few volts per kilometer to a dozen volts per kilometer and lasting for several minutes to several hours. In high-voltage and ultra-high voltage transmission systems, due to the direct grounding of the neutral point of the grid transformer, ESP will generate geomagnetic induced currents (GIC) in the

circuit formed by the east-west and long-distance transmission lines and the earth. Figure 6 shows the changes in Kp index before and after magnetic storms. It is easy to cause half wave saturation of large transformers and shorten their service life. In extreme cases, it can cause them to burn out and cause permanent damage.

At the same time, due to the global synchronization of the occurrence of magnetic storms, GIC will cause hundreds of transformers in the entire power grid to experience half wave saturation at the same time, causing some protection devices to trip and other false actions, resulting in a serious drop in the voltage of the power supply system and system collapse, leading to large-scale power outages.

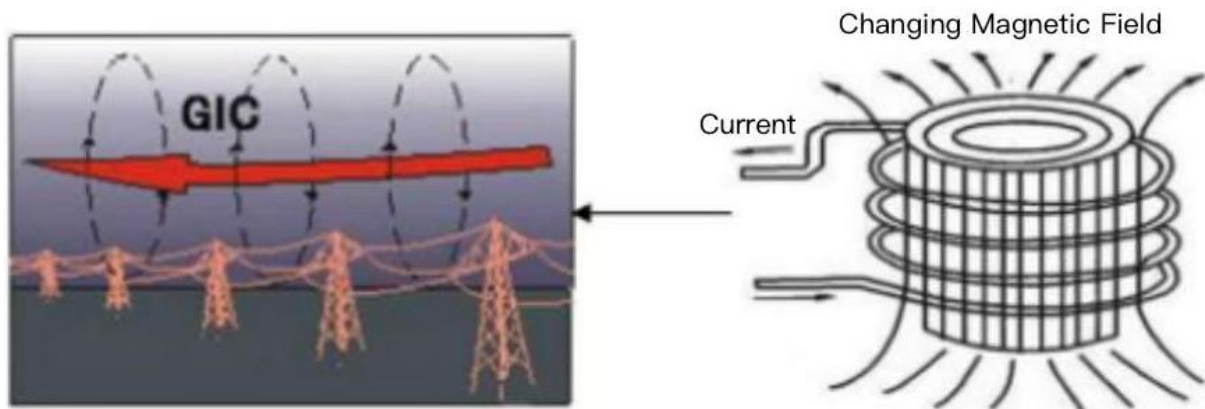


Figure 6. Changes in Kp index before and after magnetic storms.[3]

7. Forecasting

According to the advance time of the forecast, geomagnetic storm forecasting can be divided into alert, short-term forecasting, and medium-term forecasting. [5]

7.1 Alert

Warning refers to the prediction of possible geomagnetic storm levels in the coming hours, mainly including Kp index and Dst index; Mainly conducted through solar wind monitoring at point L1.

7.2 Short Term Forecasting

The lead time for short-term forecasting is 1-3 days, mainly predicting the daily value of the Ap index within the next 3 days. Forecasts are more based on the experience of forecasters. For geomagnetic storms caused by CME, satellite observations of CME can be used for forecasting; For geomagnetic storms caused by CIR, the main reference is the interplanetary solar wind and geomagnetic field changes it has previously caused.

7.3 Mid Term Forecast

The time advance of mid-term forecasting is generally a few days to several months, mainly predicting the daily value of the Ap index within the next month, relying on the prediction of the possibility of CME and CIR occurrence

8. Activity Warning

1. On November 30, 2023, the National Space Weather Monitoring and Warning Center of the China Meteorological Administration issued a geomagnetic storm warning, predicting that geomagnetic storm activity may occur on November 30, December 1, and December 2. Among them, a moderate or even severe geomagnetic storm may occur on December 1, and geomagnetic activity is expected to continue until December 2. The forecast suggests that this solar eruption activity is likely to create high intensity and brilliant auroras on December 1st, and some areas in northern China, such as Heilongjiang and Xinjiang, may see red or even green auroras.

2. On December 1, 2023, according to the Space Weather Center of the China Meteorological Administration, there may be geomagnetic storm activity in China on December.

1 and 2. Among them, on December 1, there may be a moderate or even a geomagnetic storm; On December 2nd, according to the monitoring and forecast of the National Space Weather Monitoring and Warning Center, a small to moderate geomagnetic storm may occur on December 4th due to the combined influence of the high-speed solar wind in the coronal hole and the December 1st CME.

9. Conclusion

Geomagnetic storms are global disruptions in the magnetic field of the Earth caused primarily by solar eruptions such as coronal mass ejection and high-speed solar wind streams. Geomagnetic indices, such as K, Kp, Ap and Dst, provide a means of characterising the storms' temporal evolution from initially, main and recovery phases, and can quantify the storms' overall intensity. They pose serious risks to any satellites in orbit, can increase satellite orbital drag, disrupt communication and navigation, and can induce geomagnetically induced currents in power networks, causing breakdowns and large area blackouts. Recent warning cases from late 2023 emphasise that geomagnetic storms are more than an academic issue, but a real and imminent threat to our technological world.

Nonetheless, this paper primarily describes a limited number of historical and recent occurrences without rigorous quantitative modeling of space-weather processes or systematic risk assessments of specific infrastructures. Future research and action should involve more multi-point satellites, ground-based observations, and numerical or data-driven models that will improve storm forecasting skill on time scales of hours to months. Policymakers and industry should invest in space-weather monitoring networks, develop engineering standards and mitigation strategies for satellites and electrical grids, and develop international data-sharing and emergency response protocols so that societies are better positioned to withstand and adapt to extreme geomagnetic storm events.

References

- [1] Electronic Information Basic Department of General Equipment Department. (2011). *Revealing the secrets of solar storm*. National Defense Industry Press.
- [2] Abdelmonem, A., & Kotb, A. (2019, July 14). *Magnetotelluric deep into ground water exploration* [Unpublished manuscript]. ResearchGate. https://www.researchgate.net/publication/335988565_magnetotelluric_deep_into_ground_water_exploration
- [3] Lu, G. (2021, May 17). *A sudden geomagnetic storm with $K_p=7$, the strongest in two years—Is Earth getting hotter?* [Baiké TA Shuo]. Baidu Baiké. <https://wapbaiké.baidu.com/tashuo/browse/content?id=472f163d9acf231af5e45058>
- [4] Skone, S., Yousuf, R., & Coster, A. J. (2004). Performance evaluation of the wide area augmentation system for ionospheric storm events. *Journal of Global Positioning Systems*, 3(1-2), 251–258. <https://doi.org/10.5081/jgps.3.1.251>
- [5] Electronic Information Basic Department of General Equipment Department. (2012). *Monitoring and forecasting of solar storms*. National Defense Industry Press.

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