Extreme solar phenomena: how do they impact Earth?

The Sun, the energy engine of our planetary system, provides us with light and heat, but also generates **intense phenomena** that directly impact life on **Earth.** Studying these events is crucial, as they can pose a risk to power grids and satellites, interrupting both supplies and communications.

When we talk about **extreme solar phenomena,** we refer to **large-scale energy events that take place in the solar atmosphere.** They originate from the dynamics of the magnetic field of the Sun, which accumulates energy from the convective movements of the plasma inside. When this energy is released suddenly, **eruptions and ejections** occur which, when directed toward our planet, interact with the magnetosphere and **trigger geomagnetic storms,** with clear consequences for Earth.

These storms induce geomagnetically induced currents (GICs) in terrestrial transmission lines, which can overload transformers and substations. In addition, solar eruptions release radiation that can disturb the Earth's ionosphere, altering telecommunications. This also affects global positioning systems, because they depend on the precise transmission of signals between satellites and receivers.

Effects on electricity grids

During intense geomagnetic storms, accelerated changes in the magnetic field induce transient electrical fields on the earth's surface, which generate GICs. When these currents flow through power transformers, they can cause partial saturation of the equipment, which results in **losses of efficiency,** generation of harmonics, excessive heating, and, in some cases, damage to insulation. In extreme situations, transformers can even ignite.

A notable example occurred in Hydro-Quebec, Canada, in March 1989, when a sudden geomagnetic storm caused GICs that saturated the transformers, resulting in a massive blackout lasting 9 hours. This event has been used as a basis for risk modeling and the formulation of **resilience plans today.**

The Global transformer overheating from geomagnetic storms, prepared by experts from Alliance to Feed the Earth in Disasters (ALLFED), assesses the global risks of overheating of high-voltage transformers in the event of extreme solar storms. This report suggests that a very high-intensity solar event could cause **prolonged electrical interruptions (months or even years)** in certain regions, especially in those that do not have transformer reserve capacity.

To mitigate risks and reduce exposure to GICs, several studies point to the importance of a

robust transformer design, the implementation of advanced control and protection systems, and the installation of direct current block devices.

Consequences for telecommunications and geolocation systems

Solar storms alter the electronic density of the ionosphere. As a result, abrupt changes in ionization can degrade or disrupt high-frequency communications—such as those used in **aviation** and **maritim**e sectors—according to NASA's Solar Dynamic Observatory, or impact radio waves, resulting in fading, noise, or signal loss.

Regarding the **GPS system,** the signal emitted by the satellites passes through the ionosphere before reaching the earth's surface. Variations in electronic density cause delays in the spread of signals, which reduces the accuracy of geolocation. During solar storms, these delays can cause location errors of several meters or more, depending on the intensity of the phenomenon. In certain cases, solar radiation ejections generate radio emissions that can induce failures or interruptions in GPS receivers.

Other systems that are affected are **satellites,** which experience damage to their electronic components, guidance systems, and even solar panels due to the increased exposure to solar radiation. This poses a significant threat, as many **critical infrastructures use GPS** not only for location but also for time synchronization. The loss or distortion of reference time can cause coordination errors and failures in security systems.

In May 2024, a geomagnetic storm named '**Gannon**' occurred. A series of high-power solar eruptions generated a storm that reached Earth. During that event, disruptions of GPS signals, degradation of location accuracy, and signal stability issues were recorded in the U.S. due to the effects on the ionosphere. Although no mass blackouts or large-scale electrical catastrophes were reported, anomalies and risk warnings for transformers and electrical networks were detected. This phenomenon has been considered one of the most intense of the last two decades, providing valuable information for NASA.

Lessons learned

The analysis of these events by various institutions, such as the Space Weather Prediction Center of the U.S. National Oceanic and Atmospheric Administration (NOAA), reveals that not all severe events cause blackouts, but many of them lead to minor faults or temporary disruptions. These events, taken together, represent a significant threat due to the high economic costs and the operational impacts. Furthermore, it has been observed that the **sectors that depend on high-precision GPS are particularly vulnerable,** even to minor disturbances.

However, it has been proven that **the critical electrical infrastructure of many countries is**

indeed sufficiently protected, although for extreme events, the damage and the consequences could be severe and long-lasting. It is in this context where early detection and space alerts play a key role: operators of satellites, GPS systems, airlines, or electrical networks can take preventive measures if they know that a powerful event is on the way.

In conclusion, **extreme solar phenomena represent a growing threat** to a society increasingly dependent on electrical and technological infrastructures for communications and geolocation. Although the Earth magnetosphere acts as a natural shield, intense solar storms can cause significant damage.

Investment in early detection systems, designing more resilient electrical networks, and protecting critical infrastructures are essential to mitigate the effects of these unavoidable cosmic events. To achieve this, **close collaboration is required between space agencies, technology companies, and governments** with the common goal of developing and implementing effective protection strategies. At the same time, social awareness is also important, as the growing technological dependence makes preparing for these phenomena a shared responsibility.