Space Weather From Explosions on the Sun: How Bad Could It Be?

The variable conditions in geospace driven by the Sun’s magnetic activity, known as space weather, pose an increasing threat to society [National Research Council, 2008]. Of particular concern are the infrequent and poorly known extremes.

The most powerful solar flares observed emit only a tiny fraction of the Sun’s brightness when observed at visible wavelengths. However, these explosions outshine the entire Sun by several orders of magnitude in X-ray and extreme ultraviolet channels in which the background quiescent solar atmosphere glows relatively faintly.

Continuous monitoring over 4 decades with the space-based X-ray intensity monitors on the Geostationary Operational Environmental Satellites (GOES) hints that total flare energies follow a power law of rapidly decreasing occurrence frequency with increasing total energy. A combination of the GOES X-ray records with broad spectral observations of select flares indicates that the total energy of the largest observed flares reached $10^{32}$ joules [Schrijver et al., 2012] (see Figure 1; for comparison, that energy could power a quarter million terrestrial hurricanes for a week).

Scientists can learn about possibly even larger explosions on the Sun from proxies identified in terrestrial records and from observations of Sun-like stars. With this, they can better determine what the Sun is capable of sending Earth’s way.

Proxy Records of Solar Explosions

Until recently, studies of the largest past flares had to rely on terrestrial proxies alone. Among these was nitrate, for example, produced by flare-related solar particle events (SPEs) in Earth’s upper atmosphere and stored in ice sheets. However, recent work has shown that nitrate is not useful as a proxy because of the dominance of terrestrial sources that include forest and tundra fires [Schrijver et al., 2012; Wolff et al., 2012].

In contrast, radionuclides created when solar energetic particles bombard Earth’s atmosphere are very informative, particularly when correlated across multiple records. Carbon-14 stored in tree rings and beryllium-10 recovered from polar ice cores provide continuous information with a resolution of 2–5 years for recent millennia to a decade or two on multimillennial time scales. These records show that no SPEs have happened in the past 10,000 years that are more than about 5 times as intense as the strongest events experienced in the space era when comparing the total number of solar energetic particles with energies above 30 mega-electronvolt in an event per unit area at Earth [Usoskin and Kovaltsov, 2012].

Reinterpretation of the radionuclide analyses of lunar rocks returned by the Apollo missions further constrains the frequency of the most intense SPEs. The continuous exposure of these rocks provides statistical information on the ensemble of SPEs in the balance between creation and decay of radionuclides with different half-lives. The lunar data support the terrestrial analyses: The frequency of large geospace SPEs decreases steeply.

Fig. 1. Average number of flares per year per solar or stellar hemisphere that exceed a total radiated energy $E_{bol}$. The green dashed line is a power law fit to solar data connecting feeble flares that occur outside of sunspot regions and powerful sunspot region flares; X-ray flare statistics are shown separately by the gray line [from Schrijver et al., 2012]. A horizontal dashed-dotted line at one event every 39 years marks the detection limit for space-based solar observations. The gray area identifies the uncertain range to be explored for solar extreme events, bracketed by an empirical solar limit of $10^{35}$ ergs and possibly bending down to a maximum energy of $5 \times 10^{35}$ ergs for flares detected on truly Sun-like stars [Notsu et al., 2013]. Frequencies of white-light flares observed with the Kepler satellite for stars of about solar mass, rotation rate, and brightness are shown by blue diamonds. The X-ray and extreme ultraviolet flare frequencies for the Sun-like stars K Cet and EK Dra are shown normalized downward (by factors of 120 and 4000) to the frequency expected for a solar rotation period when the background coronal brightness is used as a scale factor; the mismatch with solar data in this figure shows that although this scaling aligns flare frequencies for very active stars, it fails for stars as inactive as our Sun [Schrijver et al., 2012].

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just above the largest of the events observed in the space age, dropping to below once per millennium for a total particle dose 3 times that of the largest event observed and below once per million years at 10 times this value [Kovaltsov and Usoskin, 2014].

Data From Other Stars

In contrast to the intensities of energetic particle storms, it now appears that no such precipitous drop in frequency occurs for very large flares on stars that are otherwise much like the Sun. Light curves measured by the NASA Kepler spacecraft for tens of thousands of stars reveal that flares larger than those observed on the Sun to date occur on Sun-like stars [Notsu et al., 2013] (Figure 1): Flares on stars of nearly solar mass and internal structure and with activity presumed to resemble that of the Sun because of their matching rotation periods are consistent with a continuation of the power law spectrum of decreasing frequency with increasing flare energy.

Consequently, if the Sun is a typical star in a typical dynamo state, stellar data suggest that Earth should anticipate solar flares at $10^7$ joules roughly once per millennium and could experience a rare extreme energy of $10^9$ joules. This is based on a handful of events, all with peak brightness close to Kepler’s instrumental detection threshold, on just three stars. Thus, we are left with the question of whether these events could be artifacts rather than real flares. And, if real, do sunspot regions ever occur that are large enough to power such superflares on the Sun?

Four centuries of sunspot observations do not provide clear evidence for spotted regions thought large enough to produce such big flares [Schrijver et al., 2012], but that time base and current understanding of flares are insufficient for an unambiguous conclusion.

Geomagnetic Storm Limits

Geomagnetic storms leave no direct or proxy record to probe extremes, so scientists only have empirical data on 150 years of direct observations of variations in the strength and direction of the magnetic field at the surface of the Earth. Here scientists have to rely on theory only: The limit set by a balance of magnetic forces and plasma pressure within the Earth’s magnetic field [Vasyliūnas, 2011] suggests that the worst case geomagnetic storm can only be about twice as strong as the maximum seen during the famous 1859 Carrington event [Gonzalez et al., 2011].

Quantifying Hazards

The recent studies quantifying extremes of space weather suggest that the three different types of space weather—solar flares, energetic particle storms, and geomagnetic disturbances—have different maximum magnitudes when compared to the strongest observed to date: It may be physically impossible for geomagnetic storms to be substantially more intense than what we have already experienced, but solar energetic particle storms may be a few times stronger, while solar flares could infrequently be 10 or even 100 times more intense.

This conclusion, though intriguing, needs firming up because it involves multiple poorly known steps, including the normalization of a diversity of proxy events to a common scale and the use of large but poorly substantiated factors to correct starlight and radionuclide measurements for the energies contained in those photons and energetic particles that the instruments cannot account for. Presently, scientists do not know enough about the processes involved to determine whether, for example, the solar and stellar data in Figure 1 are consistent or whether their differences significantly differentiate the present-day Sun from the sample of flaring stars.

Despite these uncertainties, the recent new evidence suggests that extreme solar storms can be significantly more severe than what modern society has been exposed to. Society’s sensitivity to space weather is growing, but how serious space weather effects can be remains poorly quantified for any type of space storm, in particular, the largest ones that might hit Earth [National Research Council, 2008].

References


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