https://doi.org/10.20965/jdr.2022.p0230

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Extreme Solar Flare as a Catastrophic Risk

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[Received March 9, 2017; accepted December 28, 2021]

Space weather, or the disturbances of the plasma environment driven by the magnetic activities in the Sun in geospace, has become a potential source of disaster for modern society, which is increasingly dependent on its space infrastructure and large-scale power grids. Recently, independent pieces of evidence have been found that support the possibility of extremely intense space weather driven by a "superflare," a solar phenomenon that modern society has never experienced. This paper reviews state-of-art studies of superflares and their potential impacts.

Keywords: solar flares, space weather, space utilization

1. Introduction

The Sun is a variable star. The magnetic fields generated in its interior emerge through its surface to form sunspots, the concentrations of strong magnetic field that appear as dark spots. The lifespan of an individual sunspot can range from a few days to a few months, and the number of sunspots on the solar surface varies periodically over a period of about 11 years. Occasionally, the magnetic energy stored around the sunspots is suddenly released, producing an explosion called a solar flare. Intense X-ray and UV radiation, high-energy particles, and a huge amount of magnetized plasma are emitted into interplanetary space, and sometimes parts of them surge toward the Earth. The magnetic activities of the Sun and the resultant variation of the plasma environment in the outer space around the Earth (geo-space) are called space weather [1–3].

Space weather did not cause disasters in the past, as there were no notable consequences other than beautiful auroras. However, modern society is becoming more and more susceptible to space weather as it relies more and more on space assets and large-scale power grids, which suffer from such disturbances in geo-space. The most intense space weather event ever known was the so-called Carrington flare observed by English astronomer R. C. Carrington in 1859 [4]. It caused a very strong geomagnetic storm and low-latitude auroras around the world. Several studies have been done on the social and economic impacts of space weather [5–7]. It is estimated that if the same event occurred and struck the Earth now, it would cause devastating damages to satellites and ground facilities, and their restoration would take many years and trillions of dollars [5]. Indeed, the flare on July 23, 2012 is considered to have been comparable or even more intense than the Carrinton flare, though fortunately it did not hit the Earth [8].

The strongest flares have a total energy about 10^{25} J, but it is not known whether there is an upper limit to the flare energy. The Carrington flare in 1859, the total energy of which is estimated to have been 10^{25}–10^{26} J [9, 10], was also the very first solar flare observed by telescope. Because of the short history of modern space weather observation, we do not know how violent a solar flare and resultant space weather can be. Recently, striking results related to the possibility of an extremely strong solar flare have come from independent studies. One is the discovery of so-called "superflares" in solar-like (slowly rotating G-type) stars [11–13]. The energy of the superflares ranges from 10^{26} to 10^{28} J, which is more than 10–100 times larger than that of the strongest solar flares. The other is from the cosmogenic radio isotopes produced in the atmosphere by the precipitation of energetic particles (cosmic rays) from outer space. The content of the cosmogenic ^{14}C in tree rings is a good proxy for the history of cosmic rays precipitation. Using this method, Miyake et al. have found anomalously sharp increases in ^{14}C content from around 775 CE and 994 CE [14, 15]. The origin of the cosmic rays has not been identified, but one of the likely origins is extreme solar flares [16]. These findings suggest that our Sun may also produce extremely intense, super-Carringon class flares [17]. If that happens, the consequences will be catastrophic.

The aim of this paper is to review the current studies of solar superflares and their possible impacts on Earth and human activities.

2. Overview of Space Weather

The ultimate driver of space weather is the magnetic activities of the Sun. Interplanetary space is filled with a solar magnetic field, and the plasma outflow is called the "solar wind," with solar flares being the most energetic

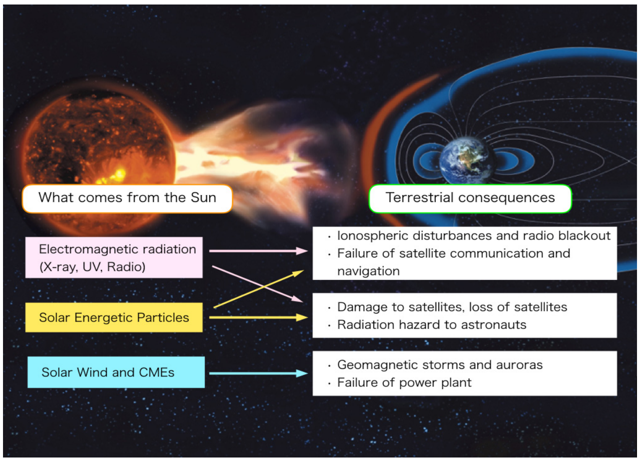

Fig. 1. Overview of space weather impacts.

source of disturbance. When a flare occurs, the energy that is released is eventually emitted into the interplanetary space in three forms: electromagnetic radiation, high-energy particles called solar energetic particles (SEP), and a cloud of magnetized plasma, called a coronal mass ejection (CME).

The impacts on geospace and the human-made infrastructure in space and on the Earth are diverse and complex. For comprehensive reviews, see [1, 5]. **Fig. 1** summarizes the major causes and consequences of solar flares.

The X-ray and UV radiation causes the enhanced ionization of the upper atmosphere of the Earth, the ionosphere. The resultant disturbance of the total electron content (TEC) affects the radio signal to and from satellites and causes trouble and failures of satellite communication and navigation. They also cause electrification of the satellites, which can damage the electrical devices onboard.

The SEPs consist of energetic protons, electrons, and heavier ions. They also cause damage to the satellites, including the degradation of electrical devices and solar panels. Furthermore, they cause radiation exposure in astronauts. The most intense SEP may cause fatal radiation exposure in astronauts if the dose is received during extravehicular activities.

The impact of the CMEs is complex due to the interaction with the magnetic field of the Earth. While velocity and mass determine the kinetic energy of a CME, the direction of the magnetic field plays an essential role in the interaction with the Earth's magnetic field. The Earth has a dipole magnetic field with positive and negative polarities located near the south and north poles, respectively, so the magnetic field of the geospace (magnetosphere) is northward. Therefore, the energy of a CME is effectively transferred to the magnetosphere of the Earth via magnetic reconnection when the CME's magnetic field is southward. The transferred energy can drive geomagnetic storms, which include various disturbances in geospace, including the enhancement of the electric current circulating around the Earth (the ring current), the acceleration of energetic particles in the radiation belt, and auroral substorms. The abrupt change of the geospace magnetic field induces the geomagnetically induced current (GIC) in large circuits on the ground, such as power grids and pipelines, resulting in significant of sometimes critical damage to transformers and the degradation of pipelines.

One can see that the hazards of space weather are to space services and assets (including astronauts), large-scale grids and pipelines. All of these are modern products. Space weather became a possible source of disaster only recently, and modern society is becoming more and more vulnerable due to the increasing reliance on technologies susceptible to space weather. As mentioned, there have been several studies done on the social and economic impacts of the strongest known solar flares [5–7]. However, the impacts of superflares stronger than the Carrington event have not been studied well.

3. Possibility of Solar Superflares

3.1. Implication from Stellar Observations

Similar to earthquakes and many other natural phenomena, the frequency of solar flares as a function of the total released energy obeys a power law. The largest solar flares (total energy $\sim 10^{25}$ J) occur about every 10 years (or once in an 11 year solar cycle). Since the history of the continuous monitoring of solar flares is still under 100 years, we do not know if or how frequently the flares with more energy occur. What can be done instead of observing the Sun 10,000 years is to observe 10,000 stars like our Sun for one year. This is the strategy of Maehara et al. and Shibayama et al. [12, 13]. Using the data of photometric observations of G-type stars from the Kepler mission [18], Shibayama et al. derived that the occurrence rate of superflares with an energy of 10^{27}–10^{28} J in the Sun-like stars (defined as the stars with a surface temperature of 5,600–6,000 K and slow rotation period of longer than 10 days) is once in 800–5,000 years [13]. Recently, Notsu et al. updated the occurrence rate of superflares with energies $\leq 5 \times 10^{27}$ J by confirming the "single" stars (i.e., there is no other star orbiting around them) with Apache Point Observatory 3.5 m telescope spectroscopic observations and correcting the steller radius estimates with Gaia-DR2 data. They concluded that superflares with energies $\leq 5 \times 10^{27}$ J could occur on G-type, slowly-rotating Sun-like stars (defined as a similar manner described above except for the rotation period of around 25 days) once every 2,000–3,000 years [19].

Of course, the G-type stars observed by Kepler are not the Sun itself. It is known that the stellar magnetic activity is well correlated with the stellar rotation; faster rotating stars are more active [20]. The difference in the rotational period is critically important. Also, there are still open possibilities that the superflares are induced by magnetic interaction with giant planets with very short orbital radii or they occur in the invisible nearby stars [11, 21, 22]. Spectroscopic observations, however, have shown that superflares do occur in the stars with rotational periods or chromospheric activity levels similar to those of the Sun [23–25].

3.2. Terrestrial Evidence

Miyake et al. have found anomalously sharp increases in ^{14}C content that date to around 775–776 CE and 993–994 CE [14, 15]. These increases have also been confirmed by several independent studies using the ^{14}C measurement in several different tree rings [26–29] as well as the measurement of another cosmogenic radioisotope, ^{10}Be, in ice cores [16, 30]. The origins of the cosmic rays have not been identified, but one of the likely origins is an extremely high SEP fluence from one or a series of solar flares [26, 31]. The total energy of the source flare is estimated to be around 10^{27} J [10]. The other candidates for the origin of such an intense and transient cosmic ray events are nearby supernovae and gamma ray bursts [14, 32, 33].

Independent proxies for the strong solar activity in the past can be found in historical documents as the records of mid- to low-latitude auroras and naked-eye sunspots [34–36]. The aurora associated with the 1859 Carrington event was witnessed all over the world, even in low-latitude regions such as Hawaii, Panama, and Japan [37, 38]. Recent surveys of the records of low-latitude aurora in historical documents suggest that at least the Carrington-class events have been common in the history [39–41].

Considering the time lag between ^{14}C production in the atmosphere and their absorption by trees [42], if one can find the historical records of latitude aurora in 774–775 CE or 992–993 CE, it will be strong support for the solar origin of the cosmic ray event.

For the 775–776 CE event, enhanced solar activity has been suggested from the historical aurora records from around that time, although no particular aurora has been associated with the same event that produced the ^{14}C event [26, 43]. For the 993–994 CE event, on the other hand, Hayakawa et al. recently found the cluster of aurora candidate records from December 26, 992 and in the period between December 25, 992 and January 15, 993 from the Korean Peninsula, Saxonian cities in modern Germany, and the Isle of Ireland [44]. More studies of both cosmogenic radioisotopes and historical records are necessary to confirm the origin of the cosmic ray events and hence the past evidence of solar superflares.

4. Potential Impacts

While quantitative evaluation of the social and economic impacts of superflares is an important yet challenging task beyond the scope of this paper, the physical parameters of space weather, such as SEP flux and CME velocity, may be estimated by extrapolating the correlation of these parameters and the total flare energy in the known flares. Recently, Takahashi et al. derived scaling laws that relate the space weather parameters and the flare energy using the empirical relation and simple theoretical arguments [45]. Based on their scaling law, here we estimate the physical parameters of CME and SEP flux of super flares.

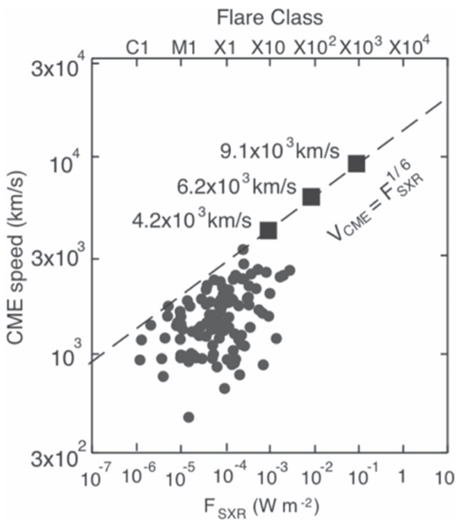

Fig. 2. Correlation of the CME speed and the soft X-ray flux. The dots are the observational data, and the dashed line indicates the scaling law. The squares show the CME speed of X10, X100, and X1000 flares, calculated by the scaling law [45].

Large flares release a significant percentage, perhaps 10%, of the total magnetic energy stored around the sunspots (active regions). Since the magnetic energy is eventually emitted in various forms, such as electromagnetic radiation, SEPs, and CMEs, estimating the total energy released based on the observational data is not a straightforward process [46], and the peak flux of soft X-rays (1–8 Å) observed by the GOES satellite is commonly used as a proxy for the total energy of flares (the so-called GOES class). Conventionally, the flares with the peak soft X-rays above 10^{-6}, 10^{-5}, and 10^{-4} W m^{-2} are called C-class, M-class, and X-class rays, respectively. For example, if the peak soft X-ray flux of a flare is 6×10^{-5} W m^{-2}, the flare is M6-class. Peak flux larger than 10^{-3} is referred to as X10, X100, and X1000 class for the peak flux of 10^{-3}, 10^{-2}, and 10^{-2} W m^{-2}. An X10 flare corresponds to the total energy of approximately 10^{25} J. The superflares with 10^{28} J are thus $\sim$X10000 class. See [47] for a more precise discussion of the relationship between the GOES class and total flare energy.

Figure 2 shows the correlation of the soft X-ray peak flux F_{SXR} and the CME speed V_{CME}. Note that the CME speed is that measured in the vicinity of the Sun through coronagraph observation. The circles are the observational data, and the dashed line indicates the scaling law $V_{CME} \propto F_{SXR}{}^{1/6}$ by Takahashi et al. [45]. While the observational data are rather scattered, it can be seen that the theoretical scaling law well explains the upper limit of the CME speed. The squares in the figure show the CME speed of X10, X100, and X1000 flares calculated

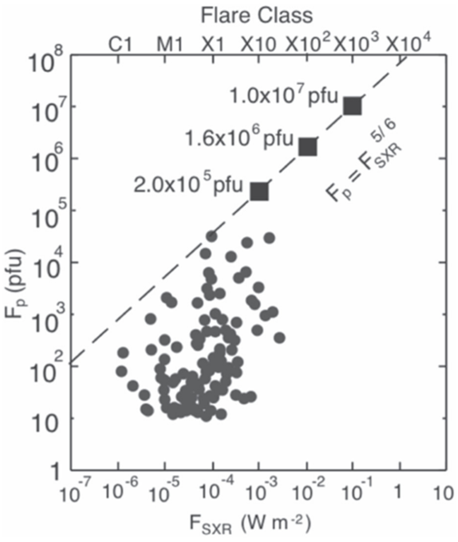

Fig. 3. Correlation of the SEP flux and the soft X-ray flux. The dots are the observational data, and the dashed line indicates the scaling law. The squares show the CME speed of X10, X100, and X1000 flares, calculated by the scaling law [45].

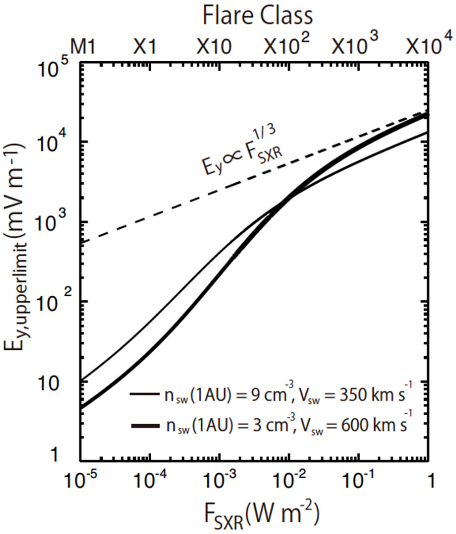

Fig. 4. The westward electric field (E_y) as a function of the soft X-ray flux E_{SXR}, calculated by the scaling law of Takahashi and Shibata [49]. The thick and thin lines fast and slow background solar winds, respectively.

by the scaling law. **Fig. 3** shows the correlation of the soft X-ray peak flux F_{SXR}, the SEP flux F_p, and the scaling law $F_p \propto F_{SXR}{}^{1/6}$. The format is the same as that in **Fig. 2**. Again the scatter of the data is large, but the scaling law well explains the upper limit.

While the CME speed of an X1000 flare is only about a factor of 2 larger than that of an X10 flare due to the weak dependence on the soft X-ray flux, the SEP flux is nearly two orders of magnitude larger. This will have a catastrophic impact on satellites in orbit. The doses of radiation received by astronauts and aircraft passengers will also be significant. Furthermore, such an extremely large SEP flux combined with enhanced UV radiation from the flare may significantly damage the ozone layer [48].

In order to estimate the intensity of the geomagnetic storms driven by the superflares, we need to know the speed, density, and magnetic field of the CMEs on the Earth. Since the CMEs undergo acceleration/deceleration as well as expansion/compression as they propagate in interplanetary space, we need to consider the physics of the CME propagation. Takahashi and Shibata [49] derived a simple analytic model of the propagation of the CME that allows us to calculate the CME parameters on the Earth once the flare parameters on the Sun and the background solar wind are given. We based the following on the theory of [49].

The intensity of a geomagnetic storm is expressed by the Dst index, which is a measure of the amplitude of the geomagnetic field variation on the ground in mid-latitude regions. The Dst has a negative value in the unit of nano Tesla during the storms. In moderate storms, the Dst is about -200 to -300 nT, and in the strongest storms, it is about -1000 nT [9, 47]. Empirically, it is known that the amplitude of the Dst is determined by the electric field E_y associated with the southward magnetic field (B_s) of the CME; $E_y = -V_{CME}B_s/c$ [47]. **Fig. 4** shows the upper limit of E_y calculated using the analytic model [49]. Then, the expected Dst can be calculated by assuming the duration of the CME passage (duration of the E_y) using the emplical model of Dst evolution [50, 51]. By assuming that the time scale is 2 hours, the Dst is calculated to be about -2000 nT for $E_y = 2000$ mV m^{-1}, corresponding to an X100 flare. However, it is not known if the empirical model for the Dst can be applied to such an extreme case.

5. Impact in Earth History

Observations of Sun-like star (slowly-rotating G type star) and terrestrial evidence indicate that, at least the Carrington-class events have been common, and even more powerful superflares may have occurred in the sun in a time scale of millennia. Fortunately for mankind, no such extreme event has hit modern civilizations.

At the same time, we are not yet sure about the magnitude of past superflare events that may have affected the Earth. Although we have no confirmable evidence of even larger flare event that can affect the surface environment of the Earth, some of the mass extinction events might have been caused by flare events, e.g., the Ordovician-Silurian (O-S) mass extinction event. A strong explosive event on a star may have caused a strong electromagnetic wave that reached the surface of Earth's oceans, causing a significant reduction in the population of trilobites. This is according to Melott et al. [52], where they insist on the possible connection with a gamma ray burst. If an extraordinary superflare occurred during that period, the extinction of species living near the surface of the ocean can be explained by abnormal UV radiation induced by the superflare. However, if these events never really occurred in the end, then there is no evidence of superflare occurrence on the Sun, meaning that solar activity may cause significant damage but not as much as other celestial or terrestrial catastrophic events, such as asteroid impacts, volcanic eruptions, and climate change, which have caused several mass extinctions. Even if this is the case, it should be noted that a strong superflare will cause catastrophic and frequent fatal events specific to our high-tech civilization, which depends upon electronic circuits and ICT technologies. Effort should be put into circumventing these modern-day catastrophes in order for us to develop a "stable and sustainable" civilization against solar flare events.

6. Discussion

As modern society's increasing dependence on its space infrastructure is a trend that will continue in the future, so will its vulnerability to space weather hazards. It is certain that an event on the level of the Carrington flare will occur again, resulting in serious economic losses. On the other hand, it is not yet certain if the >X100-class superflares really do occur on the current Sun. However, the available evidence should serve as a warning.

Can we get advanced warning of the occurrence of superflares? Theoretically, only very large sunspots that cover a few to 10 % of the solar surface can produce superflares [17], and this is consistent with stellar observations [53]. Such an anomalously large sunspot would be our alert.

Once a flare occurs, electromagnetic waves come to the Earth at the speed of light. The SEPs arrive almost simultaneously, as their energy is relativistic. Predicting the onset of flares is vitally important. However, it is still impossible to precisely predict when a flare will occur or how strong it will be, though our understanding of the basic physical mechanism has progressed significantly in the past decades [54]. On the other hand, CMEs travel much slower, giving us time to prepare for the onset of the geomagnetic storms after a flare is detected through telescopic observations. **Fig. 5** shows the expected time needed for the CME arrival after the onset of the flare. Although the CMEs from conventional flares reach the Earth one to two days after the flare onset, it takes only a half day for the CMEs to reach the Earth after superflares.

What can we do to mitigate the space weather hazards? The available option for the space infrastructure is limited, but at least the satellite operators can avoid critical operation during a severe space weather event.

For the power grid, the transformers are the most susceptible part, and these can be transiently insulated before the arrival of CMEs [7].

The continuous monitoring of solar activity and space weather is critical. However, the current operational space weather monitoring, including the solar imaging observations, is almost fully dependent on observation from satellites, which are themselves susceptible to space weather. This means we will be blind once the extreme space weather destroys the satellites. Although space observations have a lot of advantages, such as 24-hour continuous observation as well as X-ray and UV observations, it is critically important that we maintain our ground-based facilities for monitoring the sun, as they are much more resilient to extreme space weather [55].

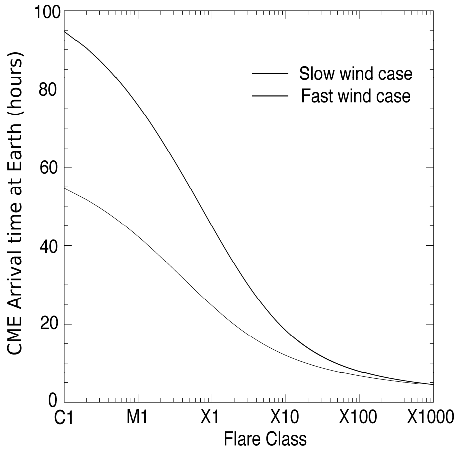

Fig. 5. The CME arrival time calculated by the scaling law of Takahashi and Shibata [49].

Acknowledgements

This work was partly supported by the JSPS KAKENHI Grant Number 16H03955, 18J23112, and 18H01254 and the Mission Research Projects of the Research Institute of Sustainable Humanosphere of Kyoto University, Japan. The authors thank H. Hayakawa, T. Tamazawa, H. Miyahara, H. Maehara, Y. Notsu, and S. Honda for their useful comments.

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