

Can Superflares Occur on Our Sun?

Kazunari SHIBATA,¹ Hiroaki ISOBE,² Andrew HILLIER,¹ Arnab Rai CHOUDHURI,^{3,4} Hiroyuki MAEHARA,^{1,5}
Takako T. ISHII,¹ Takuya SHIBAYAMA,⁶ Shota NOTSU,⁶ Yuta NOTSU,⁶ Takashi NAGAO,⁶ Satoshi HONDA,^{1,7}
and Daisaku NOGAMI¹

¹*Kwasan and Hida Observatories, Kyoto University, 17-1 Kitakazan-ohmine-cho, Yamashina, Kyoto 607-8471*

²*Unit of Synergetic Studies for Space, Kyoto University, 17-1 Kitakazan-ohmine-cho, Yamashina, Kyoto 607-8471*

³*Department of Physics, Indian Institute of Science, Bangalore, 560012, India*

⁴*National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka, Tokyo 181-8588*

⁵*Kiso Observatory, Institute of Astronomy, School of Science, The University of Tokyo,
10762-30 Mitake, Kiso-machi, Kiso-gun, Nagano 397-0101*

⁶*Department of Astronomy, Faculty of Science, Kyoto University, Kitashirakawa-Oiwake-cho, Sakyo-ku, Kyoto 606-8502*

⁷*Nishi-Harima Astronomical Observatory, Center for Astronomy, University of Hyogo,
407-2 Nishigaichi, Sayo-cho, Sayo, Hyogo 679-5313*

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Abstract

Recent observations of Sun-like stars, similar to our Sun in their surface temperature (5600–6000 K) and slow rotation (rotational period > 10 d), using the Kepler satellite by Maehara et al. (2012, *Nature*, 485, 478) have revealed the existence of superflares (with energy of 10^{33} – 10^{35} erg). From statistical analyses of these superflares, it was found that superflares with energy of 10^{34} erg occur once in 800 yr, and superflares with 10^{35} erg occur once in 5000 yr. In this paper, we examine whether superflares with energy of 10^{33} – 10^{35} erg could occur on the present Sun through the use of simple order-of-magnitude estimates based on current ideas related to the mechanisms of the solar dynamo. If magnetic flux is generated by differential rotation at the base of the convection zone, as assumed in typical dynamo models, it is possible that the present Sun would generate a large sunspot with a total magnetic flux of $\sim 2 \times 10^{23}$ Mx (= G cm²) within one solar cycle period, and lead to superflares with an energy of 10^{34} erg. To store a total magnetic flux of $\sim 10^{24}$ Mx, necessary for generating 10^{35} erg superflares, it would take ~ 40 yr. Hot Jupiters have often been argued to be a necessary ingredient for the generation of superflares, but we found that they do not play any essential role in the generation of magnetic flux in the star itself, if we consider only the magnetic interaction between the star and the hot Jupiter. This seems to be consistent with Maehara et al.'s finding of 148 superflare-generating solar-type stars that do not have a hot Jupiter-like companion. Altogether, our simple calculations, combined with Maehara et al.'s analysis of superflares on Sun-like stars, show that there is a possibility that superflares of 10^{34} erg would occur once in 800 yr on our present Sun.

Key words: stars: flare — Sun: flares — Sun: magnetic

1. Introduction

A solar flare is an explosion generated by magnetic energy released near to sunspots in the solar atmosphere (e.g., Shibata & Magara 2011 for a review). The typical amount of energy released in a flare is 10^{29} – 3×10^{32} erg (e.g., Priest 1981). Many stars show similar flares (Gershberg 2005), and sometimes the total amount of energy of a stellar flare far exceeds that of a solar flare, say, 10^{33} – 10^{38} erg (Shibata & Yokoyama 1999, 2002; Schaefer 1989), especially in young stars and binary stars, such as RS CVn. These flares are called superflares (Schaefer et al. 2000).

The first solar flare that human beings observed was a white light flare observed by Carrington (1859) and Hodgson (1859). This flare induced the largest geomagnetic storm (~ 1760 nT) in the most recent 200 yr, and caused damage to the terrestrial telegram system (Loomis 1861; Tsurutani et al. 2003). The total energy of the “Carrington flare” was estimated to be comparable to 10^{32} erg on the basis of a sketch of the white light flare (Tsurutani et al. 2003).

In more recent times, the great geomagnetic storm (~ 540 nT) on 1989 March 13 caused a widespread blackout in Quebec, Canada, and 6 million people had to spend 9 hr without electric power that night. In this case, the flare that led to the geomagnetic storm was X4.6 GOES class in soft X-ray intensity, and the total energy may have also been on the order of 10^{32} erg, considering the energy estimate of other observations of X-class flares (e.g., Benz 2008). Therefore, if superflares with energy more than 10^{33} erg would occur on our present Sun, there might be heavy damage to the terrestrial environment and our modern civilization.

Schaefer, King, and Deliyannis (2000) reported superflares on ordinary solar-type stars (F8–G8 main-sequence stars with slow rotation), but in total only 9 superflares were observed. Hence, it was not possible to discuss statistics in a reliable manner, but they argued that the occurrence frequency of superflares on solar-type stars was on the order of once in a few hundred years, though there are no historical records of superflares, or their associated hazards, in the most recent 2000 yr. Rubenstein and Schaefer (2000) have argued that solar-type

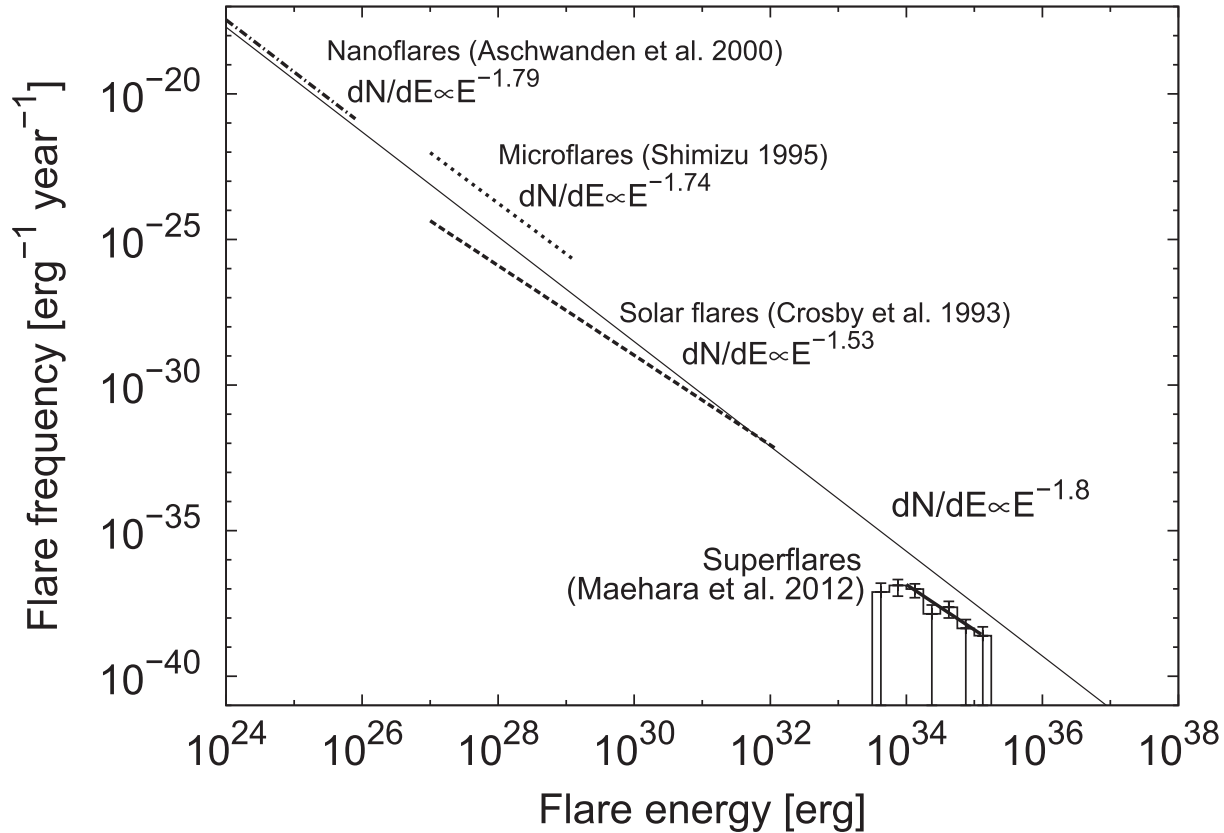


Fig. 1. Comparison between the occurrence frequency of superflares on G-type stars and those of solar flares. The solid-line histogram shows the frequency distribution of superflares on Sun-like stars (slowly rotating G-type main-sequence stars with rotational period > 10 d and the effective temperature of 5600–6000 K). The error bars in the histogram represent the square root of the event number in each bin. This distribution can be fitted by a power-law function with an index of -1.5 ± 0.3 (thick solid line). The dashed line, dotted line, and dot-dashed line indicate the power-law distribution of solar flares observed in EUV (Aschwanden et al. 2000), soft X-rays (Shimizu 1995), and hard X-rays (Crosby et al. 1993), respectively. It is interesting that superflares in Sun-like stars, solar flares, microflares, and nanoflares are roughly on the same power-law line with an index of -1.8 (thin solid line) for a wide energy range from 10^{24} erg to 10^{35} erg.

stars with a hot Jupiter-like companion are good candidates for superflare stars; i.e., the hot Jupiter may play the role of a companion star in binary stars, such as in RS CVn stars, which are magnetically very active, and produce many superflares. However, since there is no hot Jupiter near to our Sun, Schaefer, King, and Deliyannis (2000) predicted that our Sun had never generated superflares, and would never produce them in the future. Schrijver et al. (2012) also argued that flares with energy well above about 10^{33} erg are unlikely to occur, considering historical records of sunspot size over the recent 400 yr.

Maehara et al. (2012) discovered 365 superflares on solar-type stars (G-type stars) using Kepler satellite data. Among them, they found 14 superflares on Sun-like stars (slowly rotating G-type main sequence stars, which have rotational periods longer than 10 d and surface temperature of $5600 \text{ K} \leq T_{\text{eff}} < 6000 \text{ K}$). From this, they estimated that the occurrence frequency of superflares with an energy of 10^{34} erg is once in 800 yr, and that of 10^{35} erg superflares is once in 5000 yr on Sun-like stars (figure 1). If this occurrence frequency of superflares is applicable to our Sun, at some point during the next few thousand years a superflare could lead to heavy damage to Earth's environment, and be hazardous to our

modern civilization. This occurrence frequency is comparable to that of the great Earthquake that occurred on 2011 March 11 in eastern Japan. Hence, whether superflares would really occur on our Sun is important not only from an astrophysical point of view, but also from a social point of view.

In this paper, we examine whether superflares could occur on our present Sun from a theoretical point of view.

2. Big Sunspots Are Necessary Condition for Superflares

From solar observations, we already know that big flares tend to occur in big sunspot regions. Figure 2 (filled circles) shows an empirical relation between the spot size and the X-ray intensity of solar flares (Sammis et al. 2000; T. T. Ishii et al. 2012, private communication). If we assume that the X-ray intensity (GOES class) is in proportion to the total released energy by a flare, i.e., if we assume that the energy of a C-class flare is 10^{29} erg, M-class 10^{30} erg, X-class 10^{31} erg, X10-class 10^{32} erg, then this result can be interpreted as being evidence that the upper limit of the flare X-ray intensity is determined by a scaling law,

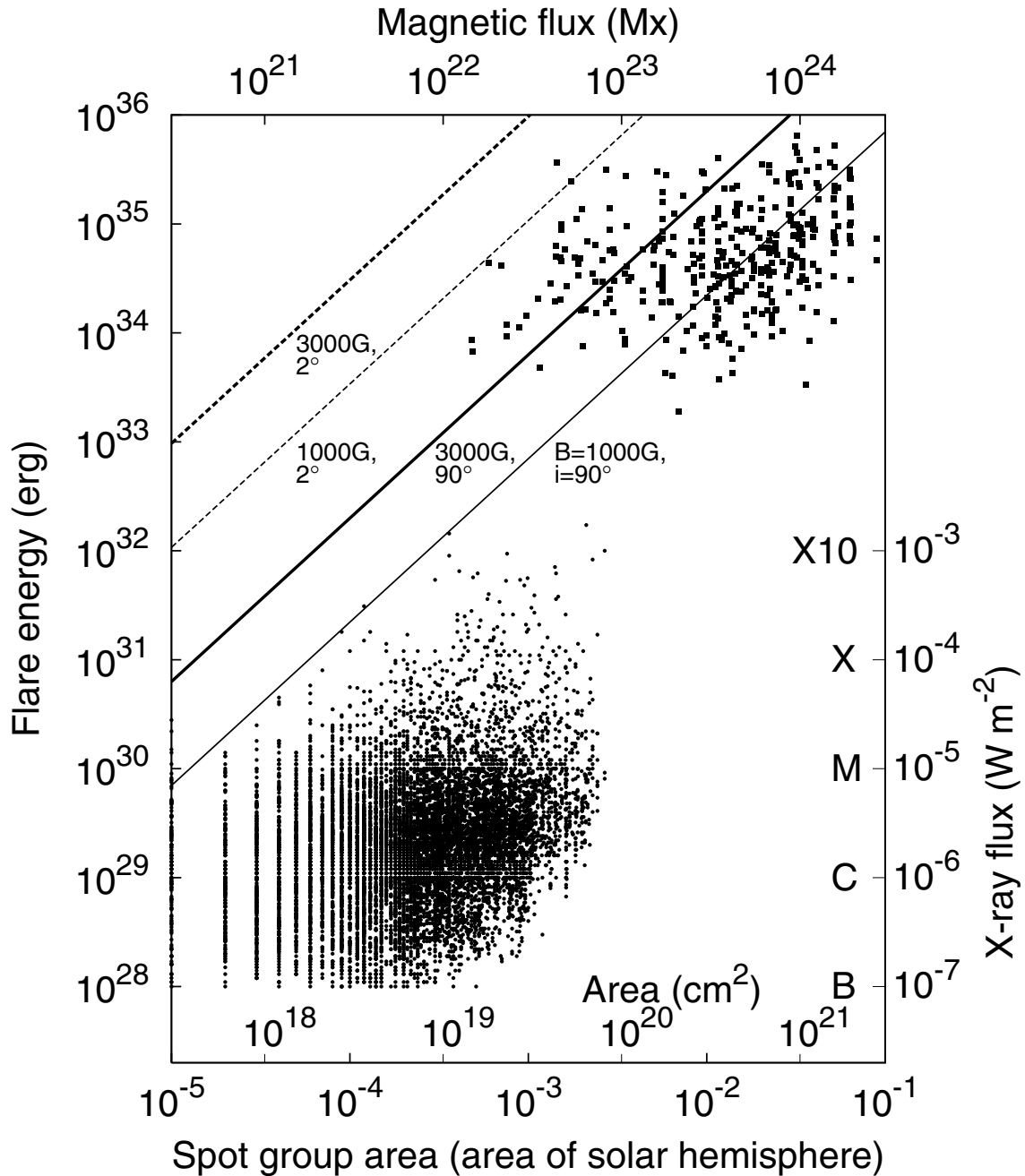


Fig. 2. Flare energy vs. sunspot area for superflares on solar-type stars (filled squares: Maehara et al. 2012) and solar flares (filled circles: Sammis et al. 2000; T. T. Ishii et al. 2012, private communication). The solar flare and sunspot region data are taken from <ftp://ftp.ngdc.noaa.gov/STP/>, and consist of data obtained in 1989–1997 (Sammis et al. 2000) and those in 1996–2006 (T. T. Ishii et al. 2012, private communication). Thick and thin solid lines correspond to the analytic relation between the stellar brightness variation amplitude (corresponding to spot area) and the flare amplitude (flare energy) obtained from equation (1) (see text) for $B = 3000$ G and 1000 G, with $i = 90^\circ$ and $f = 0.1$, where i is the inclination angle between the rotational axis and the line-of-sight. These lines are considered to give an upper limit for the flare energy (i.e., possible maximum magnetic energy which can be stored near sunspots). However, there are many superflare data points above this line. This is interpreted by Maehara et al. (2012) as meaning that these cases may correspond to the stars viewed from above the pole of the rotational axis. That is, in the case of stellar observations, the sunspot area is estimated from the apparent stellar brightness variation amplitude, so that if we observe stars from the pole, it is not possible to detect a star spot. The thick and thin dashed lines correspond to the same relation in case of nearly pole-on ($i = 2^\circ$) for $B = 3000$ G and 1000 G. Note that the superflare on solar-type stars is observed only with visible light, and that the total energy is estimated from such visible light data. Hence, the X-ray intensity in the right-hand vertical axis is not based on actual observations. On the other hand, the energy of solar flares is based on the assumption that the energy of an X10-class flare is 10^{32} erg, X-class 10^{31} erg, M-class 10^{30} erg, and C-class 10^{29} erg, considering previous observational estimates of energies of typical solar flares (e.g., Benz 2008). The values on the horizontal axis at the top show the total magnetic flux of a spot corresponding to the area on the horizontal axis at the bottom when $B = 1000$ G.

$$\begin{aligned}
E_{\text{flare}} &\approx f E_{\text{mag}} \approx f \frac{B^2 L^3}{8\pi} \approx f \frac{B^2}{8\pi} A_{\text{spot}}^{3/2} \\
&\approx 7 \times 10^{32} (\text{erg}) \left(\frac{f}{0.1} \right) \left(\frac{B}{10^3 \text{ G}} \right)^2 \left(\frac{A_{\text{spot}}}{3 \times 10^{19} \text{ cm}^2} \right)^{3/2} \\
&\approx 7 \times 10^{32} (\text{erg}) \left(\frac{f}{0.1} \right) \left(\frac{B}{10^3 \text{ G}} \right)^2 \left[\frac{A_{\text{spot}} / (2\pi R_{\odot}^2)}{0.001 \text{ cm}^2} \right]^{3/2},
\end{aligned} \tag{1}$$

where f is the fraction of magnetic energy that can be released as flare energy, B the magnetic-field strength, L the size of the spot, A_{spot} the area of sunspot, and R_{\odot} the solar radius. The sunspot area for generating X10-class flares ($\sim 10^{32}$ erg) observed in 1989–1997 (Sammis et al. 2000) was 3×10^{-4} of the half area of the solar surface, $\sim 10^{19}$ cm². The total magnetic flux for this case is 10^{22} Mx (= G cm²). Using equation (1), we find that the necessary spot size for generating superflares (4×10^{33} – 10^{35} erg) is 0.003–0.03 of the half area of the solar surface (figure 2), and the necessary total magnetic flux for superflares is 10^{23} – 10^{24} Mx.

It is interesting to note that the lifetime of sunspots (T) increases as the area of the spots (A) increases (Petrovay & van Driel-Gesztelyi 1997),

$$T \sim A/W, \tag{2}$$

where $W \sim 10$ MSH/d and MSH = Millionth Solar Hemisphere = $10^{-6} \times 2\pi R_{\odot}^2 \sim 3.32 \times 10^{16}$ cm². If this empirical relation holds when extrapolating to very big spots, the lifetime of the superflare generating spot (with a magnetic flux of 10^{24} Mx, or an area of $A \sim 10^{21}$ cm²) becomes 3×10^3 d ~ 10 yr.

It is interesting to compare our calculation with the frequency distribution of the sunspot area. Bogdan et al. (1988) showed that the sunspot area distribution obeys a log-normal distribution, while Harvey and Zwaan (1993), and more recently Parnell et al. (2009), revealed that the active region area (physically corresponding to total magnetic flux in the active region) shows a power-law distribution with an index of about -2 , which is interestingly similar to the flare frequency distribution function. According to these studies, a sunspot with an area of 3×10^{19} cm² (corresponding to 3×10^{22} Mx) occurs once in a half year. Note that this is an average frequency, since no such large spots are observed during the minima of the eleven-year cycle. If the same power-law distribution holds beyond the largest sunspot that we observed before, we find that a large sunspot with area of 10^{21} cm² (or 10^{24} Mx) occurs once in 15 yr. This frequency is clearly overestimated; such a large sunspot has never been observed in the last 2–3 centuries. On the other hand, if the power-law index is -3 (which may be fitted for an area of 3×10^{17} – 10^{18} cm² in Bogdan et al. 1988), a spot with this area would occur once in 1500 yr. Thus, for a power-law index of -2 to -3 , the frequency of a large spot with a magnetic flux of 10^{24} Mx (necessary for 10^{35} erg superflares) is roughly consistent with the frequency of 10^{35} erg superflares.

3. Generation of Magnetic Flux at the Base of the Convection Zone

Is it possible to create 10^{24} Mx with the dynamo mechanism of our Sun? Although the current theory of the dynamo mechanism has not yet been established, it is generally believed that the magnetic field generation can be explained by Faraday's induction equation using the effects of differential rotation and global plasma flow, such as global convection or circulation (e.g., Parker 1979; Priest 1981).

Faraday's induction equation is written as (Choudhuri 2003):

$$\frac{\partial \mathbf{B}}{\partial t} = \text{rot}(\mathbf{V} \times \mathbf{B}), \tag{3}$$

$$\frac{\partial B_t}{\partial t} = [\text{rot}(\mathbf{V} \times \mathbf{B})]_t \approx B_p R_p \frac{\partial \Omega}{\partial z}, \tag{4}$$

where \mathbf{B} is the magnetic flux density, \mathbf{V} the rotational velocity, Ω the angular velocity ($V = r\Omega$), B_t the toroidal component of the magnetic flux density, B_p the poloidal component of the magnetic flux density, and R_p the radius of the base of the convection zone. Here, the diffusion term is neglected. The condition that the diffusion term can be neglected near the base of the convection zone is discussed in section 4. Equation (4) can be integrated in time if the right-hand side is constant in time. Then, equation (4) becomes

$$B_t \approx B_p R_p \frac{\Delta \Omega}{\Delta z} t, \tag{5}$$

where $\Delta \Omega$ is the difference in angular velocity in the z -direction between the equator and the pole, and Δz is the latitudinal thickness of the shear layer of the differential rotation of the Sun. Hence, the total magnetic flux generated by the differential rotation in the shear layer (with a cross-sectional area of $\Delta r \Delta z$, where Δr is the radial thickness of the overshoot-shear-layer) may be written as

$$\begin{aligned}
\Phi_t &\approx B_t \Delta r \Delta z \approx B_p R_p \frac{\Delta \Omega}{\Delta z} t \Delta r \Delta z \\
&\approx B_p R_p \Delta \Omega t \Delta r \approx \Phi_p \frac{\Delta \Omega}{2\pi} t,
\end{aligned} \tag{6}$$

where Φ_p is the total poloidal magnetic flux, which is given by

$$\Phi_p \approx B_p 2\pi R_p \Delta r. \tag{7}$$

Hence, the time scale of generating the toroidal magnetic flux, Φ_t , from the poloidal magnetic flux, Φ_p , becomes

$$\begin{aligned}
t &\approx \frac{2\pi}{\Delta \Omega} \frac{\Phi_t}{\Phi_p} \\
&\approx 1.2 \times 10^9 \left(\frac{\Phi_t}{10^{24} \text{ Mx}} \right) \left(\frac{\Phi_p}{10^{22} \text{ Mx}} \right)^{-1} \left(\frac{\Delta \Omega}{5.6 \times 10^{-7} \text{ Hz}} \right)^{-1} \text{ s} \\
&\approx 40 \left(\frac{\Phi_t}{10^{24} \text{ Mx}} \right) \left(\frac{\Phi_p}{10^{22} \text{ Mx}} \right)^{-1} \left(\frac{\Delta \Omega}{5.6 \times 10^{-7} \text{ Hz}} \right)^{-1} \text{ yr}.
\end{aligned} \tag{8}$$

Here, we used the observed latitudinal differential rotation, $\Delta \Omega \sim 0.2 \Omega \sim 5.6 \times 10^{-7}$ Hz (e.g., Nandy & Choudhuri 2002; Guerrero & de Gouveia Dal Pino 2007), where Ω is the present rotation rate of $\sim 2.8 \times 10^{-6}$ Hz, while assuming

$$\begin{aligned}\Phi_p &\approx B_{\text{polarCH}} \pi R_{\text{polarCH}}^2 \approx 10 \times 3 \times (0.3 R_\odot)^2 \\ &\approx 1 \times 10^{22} \text{ Mx},\end{aligned}\quad (9)$$

which is the total poloidal magnetic flux in the polar coronal hole; the average flux density in the polar coronal hole is assumed to be $B_{\text{polarCH}} = 10 \text{ G}$, and the area of the polar coronal hole is taken to be $\pi R_{\text{polarCH}}^2 \approx 3 \times (0.3 R_\odot)^2 \approx 1.5 \times 10^{21} \text{ cm}^2$. Hence, in order to generate $\Phi_t \sim 10^{24} \text{ Mx}$, we need 40 yr. This time scale is much shorter than the time interval of the 10^{35} erg superflares, i.e., 5000 yr. The average generation rate of this magnetic flux during 40 yr is $9 \times 10^{14} \text{ Mx s}^{-1}$. The values of the polar coronal-hole field are used because the polar field of one cycle becomes the source field for the next cycle's toroidal field.

Although the above time scale is longer than the usual cycle length ($\sim 11 \text{ yr}$), it is comparable to the time scale of the Maunder Minimum ($\sim 70 \text{ yr}$). Hence, it may be possible to store and increase a magnetic flux of 10^{24} Mx (for 10^{35} erg superflares) below the base of the convection zone for 40 yr without having sunspots during that time like in the Maunder Minimum. Within a usual cycle length ($\sim 11 \text{ yr}$), because it would be possible to store a magnetic flux of $2 \times 10^{23} \text{ Mx}$, a superflare with 10^{34} erg is more easily produced.

Observations (e.g., Golub et al. 1974) show that the total magnetic flux emerging for one solar cycle ($\sim 11 \text{ yr}$) is

$$\Phi \approx B_p S \approx 2 \times 10^{25} (\text{Mx}), \quad (10)$$

and the average rate of generating magnetic flux is $d\Phi/dt \approx 5 \times 10^{16} (\text{Mx s}^{-1})$. This is much larger than the value estimated above. Therefore, it is possible to generate the magnetic flux necessary for producing superflares with 10^{35} erg , if the generated magnetic flux can be stored for $\sim 1 \text{ yr}$ for the above-mentioned parameters just below the base of the convection zone. However, this observationally estimated generation rate is not necessarily equal to the total magnetic flux stored below the base of the convection zone at one time, and hence should be considered to be an upper limit, especially if the flux created in the solar interior is able to make repeated appearances at the surface (Parker 1984).

4. Storage of Magnetic Flux Just below the Base of the Convection Zone (Tachocline)

Is it possible to store 10^{24} Mx at the base of the convection zone for such a long time (1–40 yr)? How can we reconcile the storage of magnetic flux in the stable region just below the convection zone (overshoot layer) simultaneously with the strong dynamo action due to shear rotation near the Tachocline? These points are the most ambiguous part of the present dynamo theory (e.g., Spruit 2012).

The local magnetic flux density at the base of the convection zone is thought to be 3×10^4 – $9 \times 10^4 \text{ G}$ in order to explain the emerging pattern of sunspots (Choudhuri & Gilman 1987; D'Silva & Choudhuri 1993; Fan et al. 1993). If the possible maximum flux density is assumed to be 10^5 G at the base of the convection zone (e.g., Ferriz-Mas 1996; Fan 2009), then a flux tube with circular cross-section will have a diameter of order $4 \times 10^9 \text{ cm}$ in order to carry a flux of 10^{24} Mx . The question is whether a flux tube of such a diameter can be stored at the base

of the convection zone for a few years required for the toroidal field to be built up by differential rotation.

It has been argued that magnetic flux can be stored within the overshoot layer at the bottom of the convection zone for a long time (van Ballegoijen 1982; Ferriz-Mas 1996). The depth of the overshoot layer has been estimated by various authors (van Ballegoijen 1982; Schmitt et al. 1984; Skaley & Stix 1991) to be a few tenths of the pressure scale height ($\sim 5 \times 10^9 \text{ cm}$). Skaley and Stix (1991) argued that it can be as thick as 50% of the pressure scale height. Even then, it may be difficult to store a flux tube of a diameter $4 \times 10^9 \text{ cm}$ entirely within the overshoot layer. However, we obtain such a large value of the diameter or the vertical extent of the flux tube only if we assume its cross-section to be circular.

We, of course, know that most sunspots are roughly circular. Presumably cross-sections of flux tubes rising through the convection zone become circular due to the twist around them. In fact, it has been argued that flux tubes need to have some twist around them in order to rise as coherent structures (Tsinganos 1980; Cattaneo et al. 1990). Surface observations of sunspots also indicate the presence of helical twist (Pevtsov et al. 1995). However, one of the theoretical models for explaining the helical twists of sunspots (Choudhuri 2003; Choudhuri et al. 2004) suggests that the flux tubes pick up this twist as they rise through the convection zone, and the poloidal magnetic field present in the convection zone becomes wrapped around them as they rise. If this idea is correct, then there would not be any significant twist around a flux tube at the base of the convection zone, and subsequently there would be no reason for the flux tube to have a circular cross section at the base of the convection zone.

A flattened flux tube with a thickness of 10^9 cm in the radial direction can be stored within the overshoot layer without any problem. In order to carry a flux of 10^{24} Mx , such a flux tube will have a latitudinal extension of 10^{10} cm if the magnetic field inside is 10^5 G . This latitudinal extension would correspond to a region from the equator to a latitude of about 13° at the base of the convection zone. It is certainly not impossible for such a flattened flux tube extending from the equator to 13° latitude to be stored within the overshoot layer for several years.

However, there is an energy budget problem (Ferriz-Mas & Steiner 2007). The total kinetic energy of the shear flow due to the differential rotation is estimated to be

$$E_{\text{diff}} \approx \frac{\pi}{2} R^2 d \rho_0 v_0^2 \approx 4 \times 10^{37} (\text{erg}). \quad (11)$$

Here, we assumed

$$R \approx 0.7 \times R_\odot \approx 5 \times 10^{10} (\text{cm}), \quad (12)$$

$$d \approx 10^9 (\text{cm}), \quad (13)$$

$$\rho_0 \approx 0.1 (\text{g cm}^{-3}), \quad (14)$$

$$v_0 \approx 10^4 (\text{cm s}^{-1}). \quad (15)$$

The total magnetic energy included in a flux tube (with area of $d \Delta z$, where $\Delta z \approx 10^{10} \text{ cm}$) with a total magnetic flux of

$$\Phi \approx d \Delta z B \approx 10^{24} (\text{Mx}) \quad (16)$$

is estimated to be

$$E_{\text{mag}} \approx 2\pi R d \Delta z \frac{B^2}{8\pi} \approx \frac{R}{4} \Phi B \approx 1.3 \times 10^{39} (\text{erg}), \quad (17)$$

which is much larger than the total kinetic energy of differential rotation if $B = 10^5$ G is assumed, as in the current dynamo theory (Ferriz-Mas & Steiner 2007). Hence, the necessary magnetic flux cannot be created by simple stretching of the magnetic field lines by shear motion in differential rotation.

Moreno-Insertis, Caligari, and Schüssler (1995), Rempel and Schüssler (2001), as well as Hotta, Rempel, and Yokoyama (2012) have studied a possible intensification mechanism that does not rely on mechanical line stretching through shear motions, but utilizes thermal energy: the explosion of rising flux tubes (Ferriz-Mas & Steiner 2007). This mechanism is promising because the thermal energy ($\sim 10^{13}$ erg cm $^{-3}$) is much larger than the kinetic energy ($\sim 10^7$ erg cm $^{-3}$) at the base of the convection zone. However, further studies will be necessary to establish a mechanism to generate a 10^5 G flux tube at the base of the convection zone, not only to explain superflares, but also to explain normal sunspots.

There is another problem concerning the storage of magnetic flux below the base of the convection zone, i.e., the effect of magnetic diffusivity. In the induction equations (3) and (4), we neglected the effect of diffusion. However, there is an effect of turbulent diffusion in the overshoot layer below the convection zone, because there is turbulence due to overshooting convection. In order to make the flux transport dynamo possible, the advection time for flux transport must be shorter than the diffusion time (Choudhuri et al. 1995). Since the advection time must be shorter than the solar cycle period (~ 10 yr) or superflare generating time (~ 40 yr), we find that

$$R/v \approx t_{\text{ad}} < d^2/\eta_{\text{turb}}. \quad (18)$$

Hence,

$$\begin{aligned} \eta_{\text{turb}} < d^2/t_{\text{ad}} &\approx 10^{18} \text{ (cm}^2\text{)}/[(3-12) \times 10^8 \text{ (s)}] \\ &\approx (0.6-2.4) \times 10^9 \text{ (cm}^2\text{ s}^{-1}\text{)}. \end{aligned} \quad (19)$$

These numbers are comparable to the turbulent diffusivity values assumed in previous flux transport dynamo models (e.g., Hotta & Yokoyama 2010).

Altogether, we conclude that the dynamo mechanism in the present Sun may be able to store 10^{24} Mx, which can produce superflares of 10^{35} erg based on the current idea of a typical dynamo model (e.g., Ferriz-Mas 1996; Fan 2009; Choudhuri 2011), though detailed nonlinear processes enabling both the generation and storage of 10^{24} Mx have not yet been clarified.

5. Case of Rapidly Rotating Stars

It is interesting to note that if the differential rotation rate is in proportion to the rotation rate, itself,

$$\Delta\Omega \propto \Omega, \quad (20)$$

the rate of generation of magnetic flux; i.e., the dynamo rate (f_{dynamo}) is also in proportion to the rotation rate,

$$f_{\text{dynamo}} \approx \frac{d\Phi}{dt}/\Phi \approx \Delta\Omega \propto \Omega. \quad (21)$$

Namely, the dynamo rate becomes larger when the rotation becomes faster. This is consistent with previous observations that rapidly rotating stars (such as young stars and RS

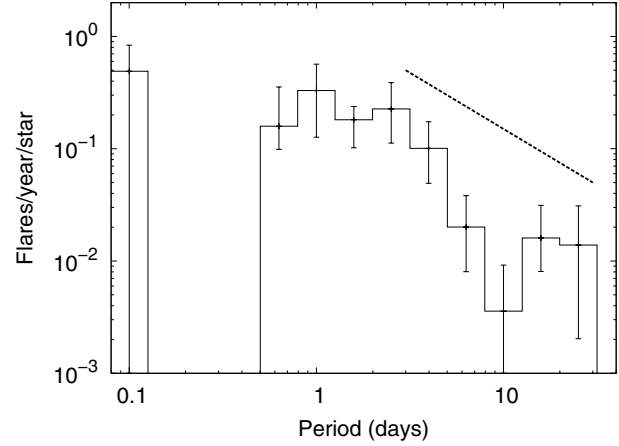


Fig. 3. Distribution of the occurrence of superflares on G-type main-sequence stars in each period bin as a function of the variation period (\sim rotational period) (Maehara et al. 2012). The vertical axis indicates the number of flares with an energy $\geq 5 \times 10^{34}$ erg per star and per year. The error bars represent the 1σ uncertainty estimated from the uncertainty in the energy estimation and the square root of the event number in each period bin. The dashed line shows the line for the occurrence frequency that is in inverse proportion to the rotational period.

CVn) are magnetically very active (e.g., Pallavicini et al. 1981; Pevtsov et al. 2003) and show many superflares (e.g., Shibata & Yokoyama 2002). Maehara et al. (2012) also found that the occurrence frequency of superflares in G-type main-sequence stars becomes larger as the rotational period of these stars becomes shorter (see figure 3). Figure 3 shows that the occurrence frequency of superflares is roughly inversely proportional to the rotation period (see the dashed line). This seems to be consistent with formula (16) if the occurrence frequency of superflares is determined by the generation rate of the magnetic flux in stars.

It should be noted that actual observations of differential rotation in late-type stars (Barnes et al. 2005; Reiners 2006) have revealed behavior different from that assumed here, i.e., the differential rotation decreases with decreasing surface temperature, and has a weaker dependence on the rotation rate. However, the evolution of the differential rotation in Sun-like stars has not yet been studied well. More detailed studies will be necessary for both observations and theories.

6. Is It Necessary to Have a Hot Jupiter for the Production of Superflares?

On the basis of an analogy with the RS CVn system, Rubenstein and Schaefer (2000) proposed that “the superflares occur on otherwise normal F and G main-sequence stars with close Jovian companions, with the superflare itself caused by magnetic reconnection in the field of the primary star mediated by the planet.” Ip, Kopp, and Hu (2004) studied the star-hot Jupiter interaction, and found that it leads to energy release via reconnection, which is comparable to that of typical solar flares. Lanza (2008) explained the phase relation between hot spots and the planets within the framework of the same idea. However, it should be noted that in order to generate

superflares, a strong magnetic field (or large total magnetic flux) must be present in the central star.

Hayashi, Shibata, and Matsumoto (1996) performed magnetohydrodynamic (MHD) simulations of the interaction between a protostar and a disk, and showed that the interaction leads to twisting of the stellar magnetic field, and eventual ejection of the magnetized plasma, similar to a solar coronal mass ejection (CME), as a result of magnetic reconnection after one rotation of the disk. This model reproduced various observed properties of protostellar flares, which are superflares with energy of $\sim 10^{36}$ erg. Nevertheless, we should remember that the eventual cause of such superflares in the star-disk interaction is the existence of a strong magnetic field (or large total magnetic flux) in the central star. If the central star's magnetic flux is small, superflares cannot exist. The differential rotation between the star and the disk can increase the magnetic field strength only by a factor of 2 or 3, because a flare/CME occurs soon after one rotation, and cannot store more magnetic flux (Hayashi et al. 1996). It is also interesting to note a similarity to solar flares; Moore, Falconer, and Sterling (2012) have shown that a flare occurs when the free magnetic energy (stored near sunspots) is about equal to the energy of the potential magnetic field.

Physically, the role of the hot Jupiter is almost the same as the role of the disk. Therefore, we can infer that the hot Jupiter can twist the magnetic field between the star and the hot Jupiter only for a short time (\sim one orbital period of the hot Jupiter); it would thus be difficult to increase the total magnetic flux of the star, itself, by a magnetic interaction alone. Lanza (2012) reached a similar conclusion by considering a more appropriate model for the interaction between the stellar and planetary magnetic fields.

Cuntz, Saar, and Musielak (2000) also proposed tidal interactions between the star and the hot Jupiter as a mechanism to enhance the magnetic activity. They argued that as a result of the tidal interaction, enhanced flows and turbulence in the tidal bulge lead to increased dynamo action. According to their calculation, the tidal force acting on the convection zone of the star by the hot Jupiter can be written as

$$F_{\text{tidal}} = 2 \frac{GM_p}{d^2} \frac{R_*}{d}, \quad (22)$$

where G is the gravitational constant, M_p the mass of the planet (hot Jupiter), d the distance between the star and the planet, and R_* the radius of the star. Then, the ratio of the tidal force to the gravitational force of the star, itself, is given by

$$\begin{aligned} \frac{\Delta g}{g} &\approx \frac{F_{\text{tidal}}}{F_{\text{gravity}}} \approx 2 \times \left(\frac{M_p}{M_*} \right) \left(\frac{R_*}{d} \right)^3 \\ &\approx 2 \times 10^{-6} \left(\frac{M_p/M_*}{10^{-3}} \right) \left(\frac{R_*/d}{10^{-1}} \right)^3, \end{aligned} \quad (23)$$

where Δg is the acceleration due to the tidal force, and g is the gravitational acceleration of the star, itself. This ratio becomes 3×10^{-6} when $M_p/M_* = 10^{-3}$, $R_* = R_\odot = 7 \times 10^{10}$ cm, and $d = 0.04$ AU = 6×10^{11} cm for a typical hot Jupiter (Cuntz et al. 2000). It is interesting to note that the ratio of the Coriolis force to the gravity force at the base of the solar convection zone is given by

$$\frac{F_{\text{coriolis}}}{F_{\text{gravity}}} \approx \frac{2V_{\text{conv}}\Omega}{GM_\odot/R_\odot^2} \approx 4 \times 10^{-7} \left(\frac{V_{\text{conv}}}{10^3 \text{ cm s}^{-1}} \right) \left(\frac{R_\odot\Omega}{2 \text{ km s}^{-1}} \right). \quad (24)$$

Hence, because the tidal force can be greater than the Coriolis force near the base of the convection zone, it may play a role in enhancing the dynamo action there.

In this case, the tidal force may enhance the global convection flow or meridional circulation flow, eventually enhancing the dynamo action, though there has been no quantitative calculation. We should remember that the physical mechanism of how the tidal force affects the dynamo action has not yet been studied in detail, including Cuntz, Saar, and Musielak (2000). Hence, the effect of the tidal force on the dynamo action remains vague.

Maehara et al. (2012) did not find hot Jupiters orbiting their 148 superflare stars, but we have to consider the possibility that small planets, invisible to Kepler, may be able to cause a similar tidal interaction. From the above calculation, we can find that the mass of the small planet must be larger than $0.2 M_J$ (Jupiter mass $\sim 10^{-3} M_\odot$) to cause the effective tidal force to be larger than the normal Coriolis force, so that the planet is able to affect the magnetic dynamo activity. If such $0.2 M_J$ planets are present near superflare stars, they would be detected with the Kepler satellite.

Altogether, we can conclude that the analogy with RS CVn cannot be successfully applied to superflare stars that are slowly rotating, but have a hot Jupiter. Namely, the reason for the high magnetic activity of RS CVn stars is fast rotation of these stars because of tidal locking. The only possible effect of a hot Jupiter on enhancing the dynamo action is the tidal interaction, but this argument cannot be applied to superflare stars observed by Maehara et al. (2012), because no exoplanets were observed near superflare stars by the Kepler satellite.

7. Conclusion

We have examined various possibilities relating to whether our Sun can produce superflares, i.e., whether our Sun can generate a big sunspot that can lead to the occurrence of superflares, using an order-of-magnitude estimate of magnetic flux generation due to the typical dynamo mechanism. Although the dynamo mechanism, itself, has not yet been established, our calculation reveals that it may be possible to generate a big sunspot (with 2×10^{23} Mx) that can lead to 10^{34} erg superflares within one solar cycle period. On the other hand, we found that it would take 40 yr to store the magnetic flux (10^{24} Mx) necessary for generating 10^{35} erg superflares. This time scale is much shorter than the time interval (~ 5000 yr) for 10^{35} erg superflares, and hence we have sufficient time to store the necessary magnetic flux (10^{24} Mx) below the base of the convection zone within 5000 yr. However, we do not at present know any physical mechanism to be able to store such a huge magnetic flux by inhibiting the emergence of magnetic flux from the base of the convection zone.

It is interesting to note here that this time scale (~ 40 yr) is comparable to the Maunder minimum period (~ 70 yr). If we succeed to make a model in which we can inhibit the emergence of magnetic flux for more than 40 yr, then we may

be able to explain both the Maunder minimum and 10^{35} erg superflares. Large sunspots and superflares are not necessarily occurring at the end of each grand minimum as a result of the field stored during the minimum, itself. Specifically, the field could be stored inside the star, and then emerges at the surface several years, or even decades, after the end of the grand minimum. Or it may emerge in several episodes producing many small or medium-sized spots along some time interval. However, it is premature to conclude whether a 10^{35} erg superflare could occur on our present Sun on the basis of current dynamo theory. Observations by Maehara et al. (2012) on 10^{35} erg superflares on Sun-like stars give a big challenge to current dynamo theory.

We also examined the role of a hot Jupiter production of superflares. Our examination shows that the magnetic interaction alone cannot explain the occurrence of superflares if the total magnetic flux of the central star is small (i.e., comparable to that of the present Sun), whereas the tidal interaction remains to be a possible cause of enhanced dynamo activity, though more a detailed study would be necessary.

Finally, it is interesting to note that Miyake et al. (2012) recently discovered evidence of strong cosmic rays in the 8th century (AD 774–775) by analyzing ^{14}C data in tree rings in Japan. The cosmic-ray intensity corresponds to a solar flare of energy $\sim 10^{35}$ erg, if the cosmic-ray source was a solar flare. Although it may be premature to relate this discovery with superflares on the Sun, it would be interesting to search for evidence of superflares by analyzing radio isotopes in tree rings and nitrate ions in antarctic ice cores.

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