Chapter 1: Introduction
Solar and stellar flares and their impact on planets

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Abstract. Recent observations of the Sun revealed that the solar atmosphere is full of flares and flare-like phenomena, which affect terrestrial environment and our civilization. It has been established that flares are caused by the release of magnetic energy through magnetic reconnection. Many stars show flares similar to solar flares, and such stellar flares especially in stars with fast rotation are much more energetic than solar flares. These are called superflares. The total energy of a solar flare is $10^{29}$ - $10^{32}$ erg, while that of a superflare is $10^{33}$ - $10^{38}$ erg. Recently, it was found that superflares (with $10^{34}$ - $10^{35}$ erg) occur on Sun-like stars with slow rotation with frequency once in 800 - 5000 years. This suggests the possibility of superflares on the Sun. We review recent development of solar and stellar flare research, and briefly discuss possible impacts of superflares on the Earth and exoplanets.

Keywords. stars:activity, stars:flare, stars:rotation, stars:solar-type, stars:starspots

1. Introduction

The first solar flare that human beings observed was a white light flare observed by Carrington (1859) and Hodgson (1859) (Fig. 1). This flare induced the largest geomagnetic storm in the most recent 200 yr, and caused several troubles in the terrestrial civilization even in the infancy of electromagnetic technology (Loomis 1861, Tsurutani et al. 2003). The time between the “Carrington flare” and the geomagnetic storm was 17 hours 40 min, suggesting average propagation speed of a coronal mass ejection (CME) ejected from the flare was about 2380 km/s, which is comparable to the speed of the fastest CMEs in recent years. Hence it has been considered that the Carrington flare was one of the most energetic flares (with energy of order of $10^{32}$ erg) observed so far (see also reviews by Cliver and Svalgaard (2004) and Schrijver et al. (2012) on the Carrington-class extreme space weather event).

After Carrington, especially since the latter half of 20th century, many solar flares have been observed in almost all electromagnetic wavelength, from radio (meter wave) to X-rays and gamma-rays (e.g., Svestka 1976, Bastian et al. 1998, Benz 2008, Fletcher et al. 2011). Typical energies of the solar flare are $10^{29}$-$10^{32}$ erg, and typical time scales are 100-10^4 sec, though there are no actual characteristic energy and time for the flare. The flare frequency statistics show that the number of flares $N$ increases with decreasing flare energy $E$ with a power-law distribution: $dN/dE \propto E^{-\alpha}$ and $\alpha \sim 1.6-2.0$ (e.g., Aschwanden et al. 2000). Recent observations revealed existence of microflares ($10^{26}$-$10^{28}$ erg) and nanoflares ($10^{23}$-$10^{25}$ erg) with a similar power-law distribution (see Fig. 12 of this paper).

The recent progress of space based solar observations in last few decades has revolutionized the solar flare research, and it has been established at least phenomenologically
that solar flares are caused by the release of magnetic energy stored near sunspots in the solar atmosphere through the magnetic reconnection (e.g., Parker 1979, Low 1996, Priest and Forbes 2000, see also Shibata and Magara 2011 for more recent review on flare MHD processes). Nevertheless, there still remains fundamental puzzles on solar flares and reconnection, such as (1) what determines the reconnection rate? (2) how can we connect the macro-scale dynamics and micro-scale plasma physics? (3) what is the triggering mechanism of solar flares?

On the other hand, many stars show flares similar to solar flares in optical, radio, and X-ray wavelengths (e.g., Guedel 2002, 2004, Gershberg 2005, Benz and Guedel 2010). Sometimes the total amount of energy of a stellar flare far exceeds that of a solar flare, say, $10^{33}$-$10^{38}$ erg, especially in young stars (Koyama et al. 1996, Feigelson and Montmerle 1998) and binary stars, such as RS CVn (Benz and Guedel 1994). These flares are called superflares (Schaefer et al. 2000). Although these stellar flares have not yet been spatially resolved, there are increasing indirect evidence of reconnection mechanism similar to that for the solar flare (Shibata and Yokoyama 1999, 2002).

It has been argued that superflares would never occur on the Sun, because astronomers believed that the necessary condition for the superflare occurrence on slowly rotating Sun-like stars is the existence of hot Jupiters near to these stars (Schaefer et al. 2000, Rubenstein and Schaefer 2000).

More recently, many superflares (with energy of $10^{33}$-$10^{35}$ erg) were discovered in solar type stars (G-type main sequence stars) without hot Jupiters, especially in Sun-like stars whose surface temperature and rotation periods are similar to those of the Sun (Maehara et al. 2011, Shibayama et al. 2013, Notsu et al. 2013b). This suggests that we cannot deny the possibility of occurrence of superflares on the Sun (Shibata et al. 2013).

In this article, we review the recent development of solar and stellar flare research from the view point of unified physical model based on magnetic reconnection mechanism, and briefly discuss possible impact of solar and stellar superflares on the Earth and exoplanets around these stars.

2.1. Solar Flares, Coronal Mass Ejections, and Plasmoid Ejections

Solar flares have been observed with Hα line from the ground based observatories, and are known to show two ribbon bright patterns in Hα images. Motivated by the observations, a standard magnetic reconnection model called CSHKP model (after Carmichael 1964, Sturrock 1966, Hirayama 1974, Kopp and Pneuman 1976) has been proposed. The CSHKP model predicts the formation of hot, cusp-shaped flare loops or arcades. The predicted cusp-shaped flare loops were indeed discovered by Yohkoh soft X-ray observations (Tsuneta et al. 1992a) (Fig. 2). Now, the standard reconnection model (CSHKP) of solar flares and flare-like phenomenon is considered established, at least, phenomenologically (Tsuneta 1996, Forbes and Acton 1996).

However, cusp-shaped flares are rather rare, and many flares do not show clear cusps. Observations show that the shape of cusp in soft X-rays is clear mainly during the long duration event (LDE) flares, that are long lived (more than 1 hours) flares, large in size, but have small frequency of occurrence. On the other hand, many flares (often called impulsive flares) are short lived, small in size, with large occurrence frequency, but show only a simple loop structure. Therefore people sometimes argued that the observed “simple loop” structure of many flares is anti-evidence of magnetic reconnection.

It was Masuda et al. (1994) who changed the entire scenario. He discovered the loop top hard X-ray source well above the simple soft X-ray loop. Since hard X-ray source is produced by high energy electrons, it provided an important evidence that a high energy process related to the central engine of flares is occurring not in the soft X-ray loop but above the loop. Hence even non-cusped loop flares may be energized by the magnetic reconnection high above the loop in a similar way as the reconnection in the cusp-shaped flares (Masuda et al. 1994). Since then, a unified model has been proposed in which the plasmoid ejection well above the loop top hard X-ray source is considered (Shibata et al. 1995) (Fig. 3).

Indeed, many plasmoid ejections have been discovered above the impulsive flares (Shibata et al. 1995, Tsuneta 1997, Ohyama and Shibata 1997, 1998, Sui et al. 2003, Kim et al. 2005, Shimizu et al. 2008). It is important to note that the strong acceleration of plasmoid occurs during the impulsive phase of the flares. This may provide a hint to
understand why and how a fast reconnection occurs in actual flares (Shibata and Tanuma 2001).

About the half of the observed coronal mass ejections (CMEs; Yashiro et al. 2004) occur in association with flares, but the other half are not associated with flares (e.g., Munro et al. 1979). This also led to a lot of confusion in the community because CMEs were thought to be fundamentally different from flares (Gosling 1993). However, Yohkoh/SXT revealed the formation of giant arcade at the feet of CMEs (Tsuneta et al. 1992b, Hudson et al. 1995, McAllister et al. 1996). These giant arcades are very similar to cusp-shaped flares in morphology, but very faint in soft X-rays and Hα, and cannot be seen in non-imaging observations of soft X-rays (such as GOES) or hard X-rays. Only high-sensitive soft X-ray (and EUV) imaging observations were able to reveal the existence of giant arcade and the association of most of the non-flare CMEs with giant arcades. Hence we can now say that both flares and non-flare associated CMEs can be unified to be basically the same type of magnetically driven explosive phenomenon (Shibata et al. 1995, Webb and Howard 2012).

2.2. Microflares, Nanoflares, and Jets

Space based solar observations revealed that the solar atmosphere is full of small scale flares, called microflares, nanoflares, and even picoflares, and that these small scale flares are often associated with jets. One of the nice example of a jet is X-ray jets discovered by Yohkoh/SXT (Shibata et al. 1992, Shimojo et al. 1996). There are many pieces of observational evidence that shows that the jets are produced by magnetic reconnection (Shibata 1999). Yokoyama and Shibata (1995, 1996) performed MHD simulation of reconnection between an emerging flux and an overlying coronal field and successfully explained the observational characteristics of X-ray jets on the basis of their simulation results. A direct extension of the 2D model to 3D MHD simulation has been carried out by Isobe et al. (2005, 2006). They found that the onset of the Rayleigh-Taylor instability at the top of the rising emerging flux leads to formation of filamentary structures and
patchy reconnection, in agreement with observations. As for the more recent development of 3D models, see e.g., Moreno-Insertis et al. (2008), Pariat et al. (2010), Archontis and Hood (2013).

From the high resolution images taken with Hinode/SOT, Shibata et al. (2007) discovered numerous, tiny chromospheric anemone jets (whose apparent foot-point structures are similar to “sea anemone” in a three dimensional space) in the active region chromosphere. The morphology of the chromospheric anemone jets is quite similar to that of the coronal X-ray jets (Shibata et al. 1992, Shimojo et al. 1996, Cirtain et al. 2007), suggesting that magnetic reconnection is occurring at the feet of these jets, although the length and velocity of these jets are much smaller than those of the coronal jets (see Takasao et al. 2013 for the most advanced 2D-MHD simulation model of jets based on chromospheric reconnection).

2.3. Unified Model: Plasmoid-Induced-Reconnection Model

Table 1 summarizes solar “flare” observations from nanoflares to giant arcades. The size and time scales range in wide values, from 200 km and 10 sec for nanoflares to $10^6$ km and 2 days for giant arcades. However, it is interesting to note that if we normalize the time scale by the Alfven time ($t_A$), then the normalized time scale becomes similar, $100 - 300 t_A$. So the “flares” mentioned in Table 1 can be unified by a common physical process i.e. magnetic reconnection. It is quite evident that although mass ejections are common in these “flares”, the morphology is quite different between the large scale and small scale flares. In large scale flares (e.g., giant arcades, LDE flares, impulsive flares), mass ejections (CMEs, filament eruptions) are bubble like or flux rope type, while in small scale flares (e.g., microflares, nanoflares), mass ejections are jets or jet-like. So what causes such morphological differences between “flares”?

Our answer to the question on morphology is as follows. According to our view (Fig. 4), the plasmoid ejection is a key process that leads to a fast reconnection (so we call “plasmoid-induced-reconnection”), since plasmoids (magnetic islands or helical flux ropes in 3D) are created naturally in the current sheets as a result of the tearing instability. In the case of large scale flares, plasmoids (flux ropes) can retain their coherent structures during the ejection even during the interaction with the ambient magnetic field. Therefore many CMEs look like the flux rope ejection. However, in the case of small scale flares, plasmoids will lose their coherent shape soon after reconnection with the ambient field, and are likely to disappear (or lose their structure) eventually after the interaction (collision) with the ambient field. As the remnant (eventually), one would expect a spinning helical jet on the reconnected field lines along with generation of Alfvén waves. We conjecture that it will explain why jets are usually observed in association with small

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**Figure 4.** A unified model (plasmoid-induced-reconnection model) of solar flares and flare-like phenomena (Shibata 1999): (a) large scale flares (giant arcades, LDE flares, impulsive flares), (b) small scale flares (microflares, nanoflares).
Table 1. Summary of Observations of Various “Flares”

<table>
<thead>
<tr>
<th>“flare”</th>
<th>length scale ($L$) ($10^4$ km)</th>
<th>time scale ($t$) (sec)</th>
<th>Alfven time ($t_A$) (sec)</th>
<th>$t/t_A$</th>
<th>type of mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>nanoflares</td>
<td>0.02 − 0.1</td>
<td>20−100</td>
<td>1 − 10</td>
<td>10 − 50</td>
<td>chromospheric anemone ejection jet</td>
</tr>
<tr>
<td>microflares</td>
<td>0.1 − 1</td>
<td>100 − 1000</td>
<td>1 − 10</td>
<td>100</td>
<td>coronal jet/surge</td>
</tr>
<tr>
<td>impulsive flares</td>
<td>1 − 3</td>
<td>60 − 3×10³ − 10⁵</td>
<td>10 − 30</td>
<td>60 − 100</td>
<td>plasmoid/filament eruption</td>
</tr>
<tr>
<td>LDE flares</td>
<td>10 − 40</td>
<td>3 $×$ 10³ − 10⁵</td>
<td>30 − 100</td>
<td>100 − 300</td>
<td>CME/plasmoid/filament eruption</td>
</tr>
<tr>
<td>giant arcades</td>
<td>30 − 100</td>
<td>10⁴ − 2 $×$ 10⁵</td>
<td>100 − 1000</td>
<td>100 − 300</td>
<td>CME/plasmoid/filament eruption</td>
</tr>
</tbody>
</table>

scale flares, although this idea should be tested through future observations. It is interesting to mention that some of the observations (Kurokawa et al. 1987, Pike and Mason 1998, Alexander and Fletcher 1999) have revealed the formation of spinning (helical) jets after flare-like phenomena (Shibata and Uchida 1986). Further, from the Hinode/XRT observations, Shimojo et al. (2007) found that an X-ray loop ejection (possibly helical loop ejection) finally led to an X-ray jet. These observations support the unified model shown in Fig. 4. (See also related recent works by Filippov et al. (2015) and Sterling et al. (2015) as supporting evidence of the unified model.)

3. Plasmoid-Induced-Reconnection and Fractal Reconnection

3.1. Plasmoid-induced reconnection

As we have discussed in the previous section, it has become clear that the plasmoid ejections are observed quite often in solar flares and flare-like events. As the spatial and temporal resolutions of the observations have become better, more and more, smaller plasmoids have been discovered in association with flares. So, how does plasmoid ejections in flares are related with the fast reconnection?

From the soft and hard X-ray observations of impulsive flares, Ohyama and Shibata (1997) found that (1) a plasmoid is ejected long before the impulsive phase, (2) the plasmoid acceleration occurred during an impulsive phase (see Fig. 5(a)). As a result of the magnetic reconnection, plasmoid formation takes place (usually about 10 min) before the impulsive phase. When the fast reconnection ensues (i.e., in the impulsive phase), particle acceleration and huge amount of energy release occurs for $\sim 10t_A$. During this process the plasmoid acceleration is closely coupled to the reconnection.

A similar relation between the energy release (and fast reconnection) and plasmoid acceleration has also been found in the case of CMEs (e.g., Zhang et al. 2001, Qiu et al. 2004) as well as in laboratory experiment (Ono et al. 2011). What is the physical understanding that can be drawn from the relation between the plasmoid ejection and the fast reconnection?

Shibata and Tanuma (2001) suggested that plasmoid ejection induces a strong inflow into the reconnection region as a result of mass conservation, and drive fast reconnection. Since the inflow (that determines the reconnection rate) is induced by the plasmoid motion, the reconnection process was termed as plasmoid-induced reconnection (Shibata et al. 1995, Shibata 1999).
Solar and stellar flares

Figure 5. (a) Time variations of the height of an observed plasmoid as well as hard X-ray intensity. From Ohyama and Shibata (1997). (b) Height-time relation of a magnetic island in a two-dimensional numerical simulation, which is supposed to be the two-dimensional counterpart of a plasmoid. Time variation of the electric field (i.e., the reconnection rate $\propto V_{\text{inflow}}$) is also plotted. From Magara et al. (1997). (c) Analytical model of plasmoid acceleration in the plasmoid-induced-reconnection model. From Shibata and Tanuma (2001). (d) Observations of a CME and associated filament eruption (Qiu et al. 2004). It is seen that the filament acceleration (+) show the time variation similar to that of electric field (reconnection rate; dotted curve). From Qiu et al. (2004).

It should be noted that a plasmoid can be formed in any current sheet if the current sheet length is longer than the certain critical length in the tearing mode instability (Furth, Killeen, Rosenbluth 1963).

During the initial stages of plasmoid formation, a plasmoid stays in the current sheet and during this stage, the plasmoid reduces the speed of reconnection significantly by inhibiting the reconnection inflow toward the reconnection region. Only when the plasmoid is ejected out of the current sheet, a substantial amount of magnetic flux can come to the reconnection region and trigger a magnetic reconnection. This facilitates the ejection of a plasmoid via strong reconnection outflow (reconnection jet), and further in turn enables to carry new magnetic flux towards the current sheet. The positive feedback between plasmoid ejection and reconnection inflow is established, so that fast reconnection occurs and eventually the plasmoid is impulsively ejected out of the current sheet with the Alfvén speed.

The 2D MHD numerical simulations (Magara et al. 1997, Choe et al. 2000, Tanuma et al. 2001) showed such dynamics very well. Figure 5(b) shows a height-time plot from a two-dimensional MHD simulation (Magara et al. 1997), in which magnetic reconnection produces an ejecting magnetic island (two-dimensional counterpart of a plasmoid). The time variation of the electric field is also plotted in the height-time plot. It is found that the electric field, that is also a measure of reconnection inflow and reconnection rate, becomes large when the magnetic island (plasmoid) is accelerated.

When comparing the MHD simulation and observations, it is assumed that the time variation of electric field in the reconnection region is closely related to the time variation of hard X-ray emissions because the electric field can accelerate particles which contribute
to producing hard X-ray emissions. The comparison suggests that the plasmoid ejection drives a fast magnetic reconnection.

Shibata and Tanuma (2001) developed a simple analytical model for the velocity of an ejecting plasmoid by assuming (1) mass conservation between inflow and outflow \( V_p W_p = V_{inflow} L_p \), and (2) the plasmoid is accelerated by the momentum added by the reconnection outflow \( \rho_p L_p W_p dV_p/dt = \rho_0 V_{inflow} L_p V_A \), where \( V_p \) is the plasmoid velocity, \( W_p \) the plasmoid width, \( L_p \) the plasmoid length, \( V_{inflow} \) the inflow velocity, \( V_A \) the Alfvén velocity, \( \rho_p \) the plasmoid density, \( \rho_0 \) the density of ambient plasma. From these simple assumptions, they obtained the plasmoid velocity,

\[
V_p = \frac{V_A \exp(\omega t)}{\exp(\omega t) - 1 + V_A/V_0}.
\]

In Equation (1), \( \omega \) represents the velocity growth rate of a plasmoid, defined as \( \omega = \rho_0 V_A/(\rho_p L) \).

The plasmoid velocity \( V_p \), its acceleration (\( a_p = dV_p/dt \)), inflow velocity \( V_{inflow} \), and the height of the plasmoid obtained from the analytical model (Shibata and Tanuma 2001) are plotted in Figure 5(c). It is interesting to note that the acceleration and the inflow velocity (or reconnection rate) derived from this simple analytical model agree well with the observations (Qiu et al. 2004, Fig. 5(d)) as well as the numerical simulation results (Cheng et al. 2003).

A detailed relation between the plasmoid velocity and the reconnection rate has been investigated by performing a series of numerical experiments (Nishida et al. 2009). An extension to 3D has also been developed by Nishida et al. (2013), and it was eventually revealed that the formation of multiple flux ropes (helically twisted field lines) in a reconnecting current sheet plays an important role in enhancing the reconnection rate. These experiments show that the reconnection rate (inflow velocity) becomes larger when the plasmoid is accelerated further by 3D effect (e.g., the kink instability) compared with 2D, whereas if the plasmoid velocity is decelerated, the reconnection rate becomes smaller. When the reconnection is inhibited, the plasmoid motion (or acceleration) is stopped.

### 3.2. Plasmoid Instability and Fractal Reconnection

On the basis of nonlinear 2D MHD simulation of the magnetic reconnection on the current sheet (Tanuma et al. 2001), Shibata and Tanuma (2001) proposed that the current sheet eventually has a fractal structure consisting of many magnetic islands (plasmoids) with different sizes (Fig. 6, see also Tajima and Shibata 1997 for an idea of fractal reconnection).

Once the current sheet has a fractal structure, it becomes possible to connect macro scale dynamics (with flare size of \( 10^9 \) cm) and micro plasma scale dynamics (with ion Larmor radius or ion skin depth of \( 10^2 \) cm). Then collisionless reconnection or anomalous resistivity can be applied to flare reconnection problems (see e.g., Cassak et al. 2005, Yamada et al. 2010, for the role of collisionless effects in reconnection).

Shibata and Tanuma (2001) presented a scenario for fast reconnection in the solar corona as shown in Figure 6(b). That is, the current sheet becomes a fractal sheet consisting of many plasmoids with different sizes. The plasmoids tend to coalesce with each other (Tajima et al. 1987, Tajima and Shibata 1997) to form bigger plasmoids. When the biggest island (i.e., monster plasmoid) is ejected out of the sheet, we have the most violent energy release which may correspond to the impulsive phase of flares.

Solar observations show the fractal-like time variability of solar flare emission, especially in microwaves (Karlicky et al. 1996, Kliem et al. 2000, Barta et al. 2008, Aschwanden 2002), and hard X-rays (Ohki 1991). The above idea of the fractal reconnection seems to explain the observations very well, since the observations suggest fragmented
energy release processes in the fractal (turbulent) current sheet. For example, Karlicky et al. (1996) showed that the temporal power spectrum analysis of the narrow band of dm-spikes of a flare show power-law spectrum, suggesting Kolmogorov spectra after transformation of the frequency scales to the distance scales.

The tearing mode instability in Sweet-Parker current sheet is studied by Loureiro et al. (2007), and is now addressed as plasmoid instability. Numerical simulations of the nonlinear evolution of the plasmoid instability has been developed significantly in recent ten years (e.g., Bhattacharjee et al. 2009).

3.3. Observational Evidence of Plasmoid-Dominated Reconnection and Fractal Reconnection

Asai et al. (2004) reported that there are multiple downflow (supra arcade downflow; McKenzie and Hudson 1999, McKenzie et al. 2013) which are associated with hard X-ray impulsive emissions. Although the origin of supra arcade downflow is still not yet understood well, the physical relation between downflow and hard X-ray emission may be similar to the relation between plasmoid ejections and hard X-ray emissions (see Fig. 5a).

By analyzing the soft X-ray images and hard X-ray emission of a flare taken with Yohkoh satellite, Nishizuka et al. (2010) found multiple plasmoid ejections with velocities of 250 - 1500 km/s. They also found that each plasmoid ejection is associated with an impulsive burst of hard X-ray emissions which are a result of high energy electron acceleration and are signature of main energy release due to the fast reconnection. Later,
Figure 7. (a) Close-up images of the reconnection site of a solar flare in six different wavelengths (171, 193, 211, 335, 94, and 131 A) of AIA at the time when the current sheet, the plasma blob, and the hot post flare loops are observed. White solid lines indicate the solar limb. (b) Schematic diagram of the flaring region. Black solid lines indicate the magnetic field. Top: the global configuration of the magnetic field. Bottom: a close-up image of the current sheet region. From Takasao et al. (2012).

Nishizuka and Shibata (2013) proposed a new theoretical model of particle acceleration at the flare loop top, considering the effect of plasmoid dynamics; namely, Fermi-type acceleration occurs when a downwardly propagating plasmoid collide with the fast mode termination shock at the top of the flare loop.

Singh et al. (2012) analyzed chromospheric anemone jets (Shibata et al. 2007) observed by Hinode/SOT, and found that all the jets they analyzed show intermittent and recurrent ejections of the jet and the corresponding brightening of the loop. Such behavior is quite similar to plasmoid ejections from large flares (e.g., Nishizuka et al. 2010). Note that chromospheric jets are considered to be a result of collisional magnetic reconnection in a weakly ionized plasma (Singh et al. 2011). Nevertheless, the time-dependent behavior of chromospheric jets is quite similar to that of coronal reconnection (collisionless reconnection), suggesting the common macro-scale dynamics, i.e., plasmoid-induced reconnection in a fractal current sheet.

Takasao et al. (2012) observed both reconnection inflow and outflow simultaneously using SDO/AIA EUV images of a flare and derived the nondimensional reconnection rate 0.055 - 0.2. They also found that during the rise phase of the flare, some plasma blobs appeared in the sheet structure above the hot flare loops, and they were ejected bidirectionally along the sheet (see Fig. 7). This is the first imaging observations of the plasmoid-dominated current sheet in a solar flare.

3.4. Flare Triggering Mechanism

What is the triggering mechanism of solar flares? This question is one of the most important questions in flare study from both scientific and application (space weather) points of view.

Chen and Shibata (2000) presented an MHD simulation model of eruptive flares and CMEs on the basis of idea from observational data analysis on the triggering of filament eruption by emerging flux (Feynman and Martin 1995). Initially, they assumed a flux rope with a filament in a stable equilibrium in 2D situation. Then, emerging flux is input from the lower boundary, which makes small scale reconnection just below the flux rope (filament). This small scale change of magnetic field configuration leads to loss of equilibrium or instability in global system, eventually leading to eruption of whole flux rope system. Kusano et al. (2012) extended this model to 3D successfully. It is
also possible to trigger global eruption of the flux rope system even when emerging flux appears in a distant place from the neutral filament if the polarity distribution is favorable for local reconnection.

Here it should be stressed that reconnection is strongly coupled to eruption of the flux rope (filament or plasmoid) as discussed above. If we inhibit reconnection, the fast ejection of the flux rope cannot be possible. Since the flux rope becomes a CME itself or a core of CME, reconnection plays essential role in fast CMEs. (See Chen (2011) for a nice review on CME models and the debate on the role of reconnection in CMEs.)

In the Chen-Shibata model, small scale reconnection (cancellation) associated with emerging flux triggers large scale reconnection in the X-point high above or far from the emerging flux region. In this sense, it can be classified as two-step reconnection model (Wang and Shi 1993). The break out model by Antiochos et al. (1999) and the tether cutting model by Moore et al. (2001) also belong to this two-step reconnection model (see also Wang et al. 2002, Nagashima et al. 2007, Schmieder et al. 2013).

Shiota et al. (2005) compared the Chen-Shibata model with Yohkoh observations of Y-shaped ejections above giant arcades (helmet streamer), finding the signature of slow and fast mode MHD shocks associated with reconnection.

Takasao et al. (2015) developed the 3D-MHD simulation model of emergence of a twisted flux tube, and reproduced the basic characteristics of the δ-type sunspot, which
4. Stellar Flares

4.1. Unified Model of Solar and Stellar Flares: Emission Measure - Temperature Diagram

The stellar flares show X-ray light curves similar to those of solar flares. The time scale and typical properties derived from soft X-rays also show some similarities to solar flares, though dynamic range of stellar flare parameters are much wider than those of solar flares. Recent X-ray astronomy satellite, such as ASCA, revealed that flares are frequently occurring in young stars, even in class 1 protostars (Koyama et al. 1996). One remarkable characteristics of these protostellar flares is that the temperature is generally high, 50 – 100MK, much hotter than the temperature of solar flares, 10 – 20MK. The total energy estimated is also huge, and amounts to $10^{36-37}$ erg, much greater than that of solar flares, $10^{29-32}$ erg.

Can we explain the protostellar flares by magnetic reconnection? The answer is, of course, yes. A part of the reason of this answer comes from our finding of empirical correlation between emission measure and temperature of solar, stellar, and protostellar flares. Figure 9 shows the observed relation between emission measure and temperature of solar flares, microflares, stellar flares (Feldman et al. 1995), and young stellar objects (YSO) flares. It is remarkable that these data show the same tendency in a very wide dynamic range. What does this relation mean?
Our answer is as follows (Shibata and Yokoyama 1999, 2002). Yokoyama and Shibata (1998, 2001) performed the self-consistent MHD simulation of reconnection with heat conduction and evaporation for the first time. From this simulation, they discovered a simple scaling relation for the flare temperature:

\[ T \simeq 10^7 \left( \frac{B}{50 G} \right)^{6/7} \left( \frac{L}{10^9 \text{cm}} \right)^{2/7} \left( \frac{n_0}{10^9 \text{cm}^{-3}} \right)^{-1/7} \text{K}. \]  

(2)

This is simply a result of energy balance between reconnection heating \((B^2 V_A^2 / 4\pi)\) and conduction cooling \((\kappa T^{7/2} / L)\) (since the radiative cooling time is much longer than the conduction time). With this equation and definition of emission measure \((EM = n^2 L^3)\), and pressure equilibrium \((p = 2n k T = B^2 / 8\pi)\), we finally obtain the following relation:

\[ EM \simeq 10^{48} \left( \frac{B}{50 G} \right)^{-5} \left( \frac{T}{10^7 \text{K}} \right)^{17/2} \left( \frac{n_0}{10^9 \text{cm}^{-3}} \right)^{3/2} \text{cm}^{-3}. \]  

(3)

We plotted this relation for constant field strength \((B = 15, 50, 150 \text{ G})\) in Figure 9. It is remarkable that these \(B = \text{constant}\) lines nicely explain empirical correlation. In other words, the comparison between observation and our theory tells that the magnetic field strength of solar and stellar flares are not so different, of order of 50-150 G. In the solar case, this value agrees well with the observations (average field strength of active region). In the case of stars, we have only limited set of observations, but these observations show a kG field in the photosphere, suggesting a 100 G average field strength in the stellar corona, consistent with our theoretical prediction.

We can also plot constant loop length lines in the diagram in Figure 9.

\[ EM \simeq 10^{48} \left( \frac{L}{10^9 \text{cm}} \right)^{5/3} \left( \frac{T}{10^7 \text{K}} \right)^{8/3} \left( \frac{n_0}{10^9 \text{cm}^{-3}} \right)^{2/3} \text{cm}^{-3}. \]  

(4)

The loop length for microflares and flares is \(10^8 - 10^{10} \text{ cm}\), consistent with the observed sizes of microflares and flares, whereas the size of stellar flare loop is huge, even larger than \(10^{11} \text{ cm}\), comparable to or even larger than stellar radius. Because of this large size, the total energy of protostellar flares become huge and their temperature becomes hotter than those of solar flares (see eq. 2). Since it is not possible to resolve the stellar flares, the large sizes of stellar flares are simply theoretical prediction at present.

Shibata and Yokoyama (2002) noted that the EM-T diagram is similar to the Hertzsprung-Russell (HR) diagram, and examined basic properties of the EM-T diagram. They found the existence of coronal branch, forbidden regions, and also showed that flare evolution track can be plotted on the EM-T diagram, similarly to stellar evolution track in HR diagram.

4.2. Superflares on Solar Type Stars

By analyzing existing previous astronomical data, Schaefer et al. (2000) discovered 9 superflares with energy \(10^{33} \sim 10^{38} \text{ erg}\) in ordinary solar type stars (G type main sequence stars with slow rotation with velocity less than 10 km/s). It was argued that the cause of the superflares is the hot Jupiter orbiting near to these stars (Rubenstein and Schaefer 2000), and thus concluded that the Sun has never produced superflares, because the Sun does not have a hot Jupiter (Schaefer et al. 2000).

Maehara et al. (2012) analyzed the photometric data obtained by the Kepler space telescope (which was intended for detecting exoplanets using transit method), and found 365 superflares on 148 solar type stars. Figure 10 shows a typical example of a superflare observed by Kepler, which shows the spike–like increase (1.5 percent) in stellar brightness.
for a short time (a few hours). It should be remembered that even one of the largest solar flares in recent 20 years (X18 class solar flare in 2003) showed only 0.03 percent solar brightness increase for 5 to 10 minutes. The total energy of this superflare was estimated to be around 10^{35} \text{ erg}, 1000 times larger than the largest solar flare (10^{32} \text{ erg}).

It is also interesting to see in Figure 10 that the stellar brightness itself shows significant time variation with amplitude of a few percent with characteristic time of 10 to 15 days. It is remarkable that almost all superflare stars show such a time variation of the stellar brightness. Maehara et al. (2012) interpreted that the stellar brightness variation may be caused by the rotation of a star with big starspots (Fig. 10).

Notsu et al. (2013b) developed this idea in detail using the model calculation of the brightness change of the rotating star with big starspots. If this interpretation is correct, we can indirectly measure the rotation period of stars and the size of star spot (or total magnetic flux assuming the magnetic flux density is the same as that of the sunspot, 1000 to 3000 \text{ G}). Since a big spot can store huge amount of magnetic energy around it, it is reasonable to find that almost all superflare stars show stellar brightness change of the order of a few percent or more as indirect evidence of big spots necessary for occurrence of superflares.

According to Shibata et al. (2013), the maximum energy of solar flares in a spot with magnetic flux density $B$ and an area $A$ has an upper limit determined by the total magnetic energy stored in a volume $A^{3/2}$ near the spot, i.e.,

$$E_{\text{flare}} \sim f E_{\text{mag}} \simeq f \frac{B^2}{8\pi} A^{3/2} \simeq 7 \times 10^{32} [\text{erg}] \left( \frac{f}{0.1} \right) \left( \frac{B}{10^3 \text{ G}} \right)^2 \left( \frac{A}{3 \times 10^{19} \text{ cm}^2} \right)^{3/2}$$

$$\simeq 7 \times 10^{32} [\text{erg}] \left( \frac{f}{0.1} \right) \left( \frac{B}{10^3 \text{ G}} \right)^2 \left( \frac{A/2\pi R_{\text{sun}}^2}{0.001} \right)^{3/2}$$

(5)

where $f$ is the fraction of magnetic energy that can be released as flare energy.

Figure 11 shows the empirical correlation between the solar flare energy (assuming that GOES X-ray flux is in proportion to flare energy) versus sunspot area. We see that the theoretical relation (upper limit is used in eq. (5)) nicely explains observed upper limit of flare energy as a function of sunspot area. We also plotted the superflare data on the Figure 11. It is interesting to see that there exist many superflares above the theoretical upper limit. One possible solution of this apparent discrepancy is that these stars (above an upper limit) may be pole-on stars. Namely, if we observe stars from the
pole, we tend to estimate smaller size of star spot, because the brightness change of stars (due to rotation) become small when viewed from rotating poles.

Later, Notsu et al. (2015a, b), using spectroscopic observations of 34 superflare stars, confirmed the interpretation, in addition to the confirmation of the real rotation velocity of these 34 stars (see also Notsu et al. 2013a, Nogami et al. 2014, Honda et al. 2015).

Figure 11 shows that both solar and stellar flares are caused by the release of magnetic energy stored near spots. Figure 9 (EM-T diagram) along with Figure 11 (energy vs magnetic flux diagram) makes us sure that in a statistical sense the stellar flares are actually caused by the magnetic reconnection.

Maehara et al. (2015) analyzed the short time cadence data (1 min) taken by the Kepler mission, and found that the duration of superflares scales with flare energy \(E\) as \(t_{\text{flare}} \propto E^{0.39}\), which is similar to the correlation between the duration of solar flares and X-ray fluence \(E\) observed with the GOES \(t_{\text{flare}} \propto E^{1/3}\) (Veronig et al. 2002). This correlation is interesting because the reconnection model of flares predict that the flare energy and duration scales with the length \(E \propto L^3\) and \(t_{\text{flare}} \propto L\), since the flare duration is basically determined by the inverse of the reconnection rate, of order of 100 \(t_A = 100 L/V_A\). From these relations, we find \(t_{\text{flare}} \propto L \propto E^{1/3}\). This explains both solar and stellar flare observations. It provides another evidence of the magnetic reconnection model for \textit{spatially unresolved} stellar flares.

What is the frequency of solar flares and stellar superflares? Figure 12 shows the occurrence frequency of flares as a function of flare energy, for solar flares, microflares,

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**Figure 11.** Flare energy vs sunspot area (Maehara et al. 2015). Thick and thin solid lines in this figure represent Equation 5 for \(f = 0.1, B = 3,000\) and 1,000 G, respectively. Filled squares and small crosses show data of superflares on solar type stars, while small dots are solar flare data.
nanoflares and also superflares on Sun-like stars. It is remarkable to see that superflare frequency is roughly on the same line as that for solar flares, microflares, and nanoflares,
\[ \frac{dN}{dE} \propto E^{-2} \]  
suggesting the same physical mechanism for both solar and stellar flares. It was found that the occurrence frequency of superflares of $10^{34}$ erg is once in 800 years, and that of $10^{35}$ erg is once in 5000 years on Sun-like stars whose surface temperature and rotation are similar to those of the Sun.

It should be noted here that there were no evidence of hot Jupiters around the superflare stars, suggesting the possibility that superflares may occur on the Sun (Nogami et al. 2014).

Shibayama et al. (2013) extended and confirmed the work by Maehara et al. and found 1547 superflares on 279 solar type stars from 500 days Kepler data. Shibayama et al. found that in some Sun-like stars the occurrence rate of superflares was very high, 4 superflares in 500 days (i.e., once in 120 days).

It is interesting to note that large cosmic ray events in 7th and 9th century are found from tree ring (Miyake et al. 2012, 2013). Although the source of this cosmic ray is a matter of further investigation, the possibility that such event is caused by a solar superflare cannot be ignored. The frequency of the large cosmic ray events is pretty much consistent with the superflare frequency.

What is the relation between flare energy and rotational period of stars? Figure 13 shows the flare energy vs. the brightness variation period (interpreted as the rotation period of each star). It is remarkable that the maximum energy of stellar flares are almost independent of their rotational period, against expectation. Figure 13b also shows distribution of the occurrence frequency of flares as a function of the brightness variation period (rotational period of each star). This figure shows that as a star evolves (and its rotational period increases), the frequency of superflares decreases. Hence expected average coronal X-ray luminosity would also decrease with increasing rotational period, which agrees well with our previous observations of solar type stars. One amazing discovery from Figure 13 is that the superflare (with energy comparable to $10^{34}$-$10^{35}$ erg)
Figure 13. (a) Scatter plot of the flare energy vs. the brightness variation period (interpreted as the rotation period of each star). The period of the brightness variation in this figure was estimated by using the Kepler data. (b) Distribution of the occurrence frequency of flares as a function of the brightness variation period (rotational period of each star). The vertical axis indicates the number of flares with energy $5 \times 10^{34}$ erg per star per year. The frequency distribution of superflares saturates for periods shorter than a few days. It is interesting to note that a similar saturation is observed for the relationship between the coronal X-ray activity and the rotation period of stars (Randich 2000). From Notsu, Y. et al. (2013b).

can occur on slowly rotating stars like our Sun, even if the frequency is very low (once in a few thousand years).

If a superflare with energy $10^{34} - 10^{35}$ erg (i.e., 100 - 1000 times larger than the largest solar flares ever observed, such as the Carrington flare) occur on the present Sun, the damage that such a superflare can cause to our civilization would be extremely large. Hence it is very important to study the basic properties of superflares on Sun-like stars to know the condition of occurrence of superflares and to understand how the superflare-producing stars are similar to our Sun.

In this regard, Balona et al. (2015) examined oscillations in light curves of stellar superflares using short-cadence Kepler data, and detected flare loop oscillations similar to solar flare loop oscillations (e.g., Nakariakov et al. 2006) in a few stars, but did not find conclusive evidence as yet for flare induced global acoustic oscillations (starquakes) (Kosovichev and Zharkova 1998). This kind of comparative studies between solar flares and stellar superflares will be important to reveal the difference and similarity of physical conditions of our Sun and superflare stars.
It should be noted that stellar flares observed by Kepler are all “white light flares”, and that the physics of solar white light flares have not yet been understood well and hence one of the hottest topics of the present flare research (e.g., Heinzel and Kleint 2014, Kowalski et al. 2015).

It will also be important to study the difference and similarity between solar type stars (G type dwarfs) and non-solar type stars. Candelaresi et al. (2013) and Balona (2015) studied superflares on non-solar type stars (i.e., A, F, K, M type stars). According to the detailed study by Maehara et al. (2015, in preparation), if we determine the size of spots, the maximum flare energy and frequency are uniquely determined, independent of the stellar properties (surface temperature and rotational period). (Instead, the size of spots strongly depend on the surface temperature and rotational period.)

5. Impacts of Superflares on the Earth and Exoplanets

If a superflare with energy $10^{34} - 10^{35}$ erg would occur on the Sun or Sun-like stars, what would be expected on the environment of the Earth and exoplanets orbiting in a habitable zone around the Sun-like stars?

It has already been discussed that if the Carrington-class flare would occur, our civilization would suffer various disasters, such as electric power outage, radio communication troubles, damages of many artificial satellites, and dangerous radiation exposure to astronauts and airline passengers (e.g., Baker 2004, Tsurutani and Lakhina 2014, Gopalswamy et al. 2015). Hence much more severe disasters would occur all over the world if the super-Carrington flare occur on the Sun.

What would happen on the Earth, if the super-Carrington flare occur in ancient days? The maximum brightness (in visible light) of $10^{35}$ erg superflare is only a few percent larger than the average brightness of the Sun (Fig. 10), so that there is nothing changed in the terrestrial climate in a short time scale just when the superflare occurs.

However, UV and EUV would increase more than 10 percent when the superflare occurs. We can expect the average solar/stellar activity would be significantly increased (see the flare frequency of the most active Sun-like stars in Fig. 12). They affect the upper atmosphere of the Earth and exoplanets significantly.

Further, considering the empirical rule that the sunspot lifetime increases with increasing with the size of sunspot, we can expect the lifetime of large spots on superflare stars is comparable to 10 years (Shibata et al. 2013). Then long term climate variation may be triggered by the prolonged hyper-activity of the Sun and stars. (It is interesting to note that Saar and Brandenburg (1999) reported the existence of hyper-active phase of stellar activity cycle in some stars.) Even the enhanced visible light variation may occur as a result of the increased spot area or faculae for such a long time. (Consider what would happen if the solar brightness will be decreased by a few - 10 percent for 10 years by the effect of large spots.)

There is another effect of the superflare. That is the enhanced high energy particles by the superflare. It is not easy to estimate the radiation dose of superflare particles at the ground level but we think it is not much (less than 40 mSv). Hence we think there is no significant effect of solar energetic particles on the life on the ground in a short time scale (Takahashi et al. 2015, in preparation).

However, it is known that the solar energetic particles (protons) can destroy the ozone layer in the high latitude regions, since the energetic protons collide with Nitrogen to form NOx molecules, which eventually destroy ozone ($O_3$) molecules.

Figure 14 shows time evolution of the ozone column depth in an Earth-like exoplanet orbiting in the habitable zone around an M-type dwarf (Hawley et al. 1995) when a
superflare occur on the M-type star (Segura et al. 2010). This calculation shows that the effect of the flare (protons and UV) is short (only for a few years or so), so that flares may not present a direct hazard for life on the surface of an orbiting habitable planet. Further studies will be necessary to predict the consequence and impacts of superflares on the Earth and exoplanets with various atmospheric conditions.

The study of superflares on the Sun and stars are important not only for the survivability of our society and civilization on the present and future Earth, but also for the habitability and evolution of life on exoplanets (as well as on the past Earth).

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