Astrophys Space Sci (2015) 359:4
DOI 10.1007/s10509-015-2466-5

ORIGINAL ARTICLE

Towards understanding the frequency distribution of solar flares—part 1: a Stochastic-Diffusive model of solar flares

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Received: 15 February 2015 / Accepted: 27 July 2015 / Published online: 4 August 2015

Abstract Systematic relationships of the subclass-averaged rise, decay times and durations of flare events as a function of the logarithmic peak flux ($\ln f$) are investigated, employing the soft X-ray flares observed by GOES during the period from September 1975 to October 2014. Different behaviors are found before and after 1997. Since 1997 they all vary linearly with $\ln f$, obeying the RV model. However, prior to 1997 they vary quadratically with $\ln f$, implying a different energy storage/release process of flaring. The discrepancy may be related to the variation in the turbulence in the corona caused by the weakening magnetic field strength in the recent two decades. This motivates us to propose a Stochastic-Diffusive model for explaining the above result, by assuming that the temporal rate of flare energy resulted by external forces is proportional to the total energy already stored in the flare system and inversely proportional to the size scale of diffusion.

Keywords Sun: activity · Sun: flares · Solar corona · Sun: X-rays, gamma rays · Methods: analytical · Turbulence

1 Introduction

Solar flares are one of the powerful eruptive events in solar activities, intimately associated with solar energetic particles and coronal mass ejections (Fletcher et al. 2011). They are closely related to the active regions with strong magnetic gradients (Wang et al. 1994), highly sheared transverse magnetic fields (Rausaria et al. 1993; Chen and Shibata 2000), flux emergences (Schmieder et al. 1997; Chen and Shibata 2000; Zhang 2006), and flux cancellations (Wang and Shi 1993; Zhang and Wang 2001). They appear some behaviors also found in other solar activities, such as the hemispheric asymmetry (Mursula and Hiltula 2004; Deng et al. 2013a,b; Feng et al. 2013; Du 2015) and the quasi-periodic behavior (Feng et al. 2013; Deng et al. 2015). Besides, the rapid rotation of the sunspot is also found to be related to the occurrence of the eruptive phenomena. It can cause twist to be injected through the chromosphere into the corona, and the twisted flux tubes may store sufficient energy to trigger the flares (Yan and Qu 2007; Yan et al. 2009).

It is now widely accepted that the flare results from the rapid release of the free energy stored in non-potential magnetic fields in the active regions (Zirin and Tanaka 1973; Hagyard et al. 1984). However, how the magnetic energy is stored and released still remains not well understood. In fact, one of the most puzzled problem in solar physics is about the solar coronal heating mechanism, which may be classified as wave (alternating current) heating mechanism (Davila 1987; Jess et al. 2009; van Ballegooijen et al. 2011), reconnection (direct current) heating mechanism (Parker 1988; Rappazzo et al. 2008), and a recent magnetic-gradient pumping mechanism (Tan 2014). Most heating mechanisms aim to the energy conversion process of how the magnetic energy is stored and released. In the current study, we focus on the temporal evolutional behavior of flares in effect.

Studying the relationships between the peak flux (f) and the related temporal parameters of solar flare events is useful in understanding the process of flaring (Parker 1988; Morales and Charbonneau 2010; Kahler 2013). The temporal parameters of solar flares observed at various wavelengths have been investigated for a long time (Culhane and Phillips 1970; Drake 1971; Thomas and Teske 1971; Pearce and Harrison 1988). For example, solar flares tend to oc-

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cur in intermittent impulses at any time (Rosner and Vaiana 1978; Lin et al. 1984; Parker 1988). Culhane and Phillips (1970) divided the X-ray bursts into two categories, impulsive and gradual, and suggested that there might be two different mechanisms of coronal heating related to them. Drake (1971) pointed out that the occurrence frequency of rise rime (T_a) followed an exponential law.

The frequency distributions of various parameters (Aschwanden et al. 2014) have been found to obey power laws in a variety of phenomena such as radio bursts, soft X-rays (*SXR*), hard X-rays, solar energetic proton events, and so on (Das et al. 1997; Drake 1971; Datlowe et al. 1974; Hudson 1978; van Hollebeke et al. 1975; Li et al. 2012; Le et al. 2014a; Marković and Gros 2014). In order to explain the power-law distribution of solar flare energy, Rosner and Vaiana (1978) proposed a model (RV model, hereafter) by assuming that the probability distribution of *SXR* flares follows Poisson statistics and that the e-folding time for energy storage is constant. Lu and Hamilton (1991) interpreted the power law of solar flares as a critical state of a self-organized system (Bak et al. 1987). Aschwanden and Freeland (2012) proposed a fractal-diffusive self-organized criticality model in attempting to explain the power-law index.

Since major flares tend to have longer durations (T) than minor ones do (Veronig et al. 2002; Temmer et al. 2003; Kay et al. 2003; Du and Wang 2012; Le et al. 2014b), a systematic relationship should be expected between f and T. However, in an earlier study Pearce and Harrison (1988) found no evidence to support the statement that brighter (weaker) flares should be longer-(short-)lived. As flaring phenomena are related to the convective turbulence (Rosner and Vaiana 1978; Parker 1988; Lu and Hamilton 1991; Cattaneo et al. 2003; Aschwanden 2012), the relationships between the peak flux and the related temporal parameters are very loose (Pearce and Harrison 1988; Kay et al. 2003).

This paper is the first in a series of articles dealing with the frequency distribution of solar flares. In the following papers, we will analyze the probability statistics and power-law distribution of solar flares. In the current presentation, we investigate the systematic relationships of the rise time (T_a), decay time (T_d) and duration (T) of *SXR* flares with the peak flux (f). For this purpose, these parameters should be averaged over each subclass in order to reduce the underlying random errors in the parameters (Pearce and Harrison 1988; Kay et al. 2003). Besides, as the recent two solar cycles (23 and 24) showed an unexpected low activity (Usoskin et al. 2007; Hathaway and Rightmire 2010; Zhdankin et al. 2014) and the earlier flare times prior to 1997 were taken from the Hα events if available (Veronig et al. 2002), different behaviors might be seen before and after 1997. Therefore, we examine the relationships using the data separately since and prior to 1997.

The data and parameters used in this study are described in Sect. 2. After simply analyzing the scatter plot of f versus T_a as an example (Sect. 3), we examine the systematic relationships of the averaged T_a, T_d, T and integrated flux (E) over subclass with f of flare events since 1997 (Sect. 4). In Sect. 5, we investigate the relationships of the averaged T_a, T_d and T with f prior to 1997. Then a model is proposed in attempting to explain these relationships (Sect. 5.1) followed by discussions and conclusions in Sect. 6.

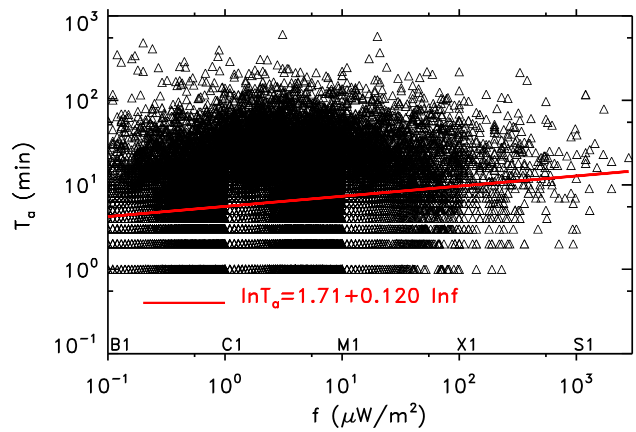

Fig. 1 Scatter plot of rise time (T_a) against peak flux (f). The *red solid line* indicates the linear fit of $\ln T_a$ to $\ln f$

2 Data set

The data of soft X-ray (*SXR*, 1–8 Å) flares based on *Geostationary Operational Environmental Satellite (GOES)* are taken from the catalog compiled by the *Solar Geophysical Data (SGD)*,[1] available from September 1975 to October 2014. The catalog includes the start time, peak time, end time, peak flux (f, in μW/m^2) and integrated flux (E, in μJ/m^2, since 1997 only) for each flare event, from which the rise time (T_a, from start to peak), decay time (T_d, from peak to end) and duration ($T = T_a + T_d$, in minutes) of the flare event can be derived. The flares of class higher than X10 are called as super or S-class flares (Tan 2011) and their subclasses are adjusted accordingly. For instance, an X28 flare is renamed as an S2.8, etc. The records labelled by 'C0.0' have been removed. Thus, we have 73126 records from September 1975 to October 2014, including 21 S-, 466 X-, 6172 M-, 45523 C- and 20944 B-class flares.

3 Scatter plot of the rise time against peak flux

As an example, Fig. 1 shows the scatter plot of the observed rise time (T_a) against peak flux (f). The straight line indicates the linear fit in the logarithmic scale by the following

[1] ftp://ftp.ngdc.noaa.gov/STP/space-weather/solar-data/solar-features/solar-flares/x-rays/goes/.

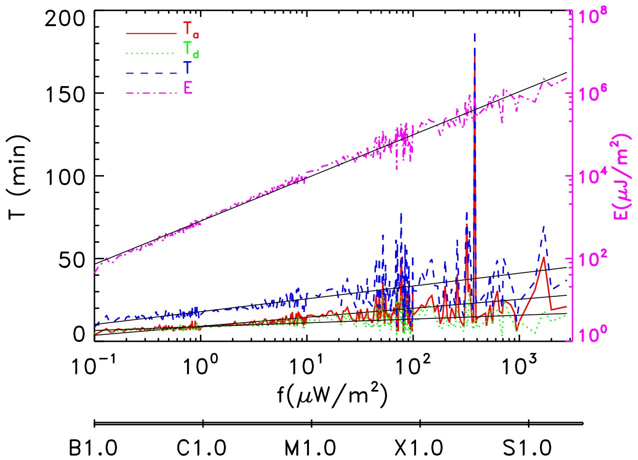

Fig. 2 Averaged rise time (T_a, *solid line in red*), decay time (T_d, *dotted line in green*), event duration (T, *dashed line in blue*) and integrated flux (E, *dash-dotted line in purple*, right-hand scaled) of *SXR* flares as a function of the peak flux (f) since January 1997

equation:

$$\ln T_a = 1.714 \pm 0.004 + (0.120 \pm 0.002) \ln f, \tag{1}$$

or, equivalently,

$$T_a = (5.5 \pm 0.7) f^{0.120 \pm 0.002}. \tag{2}$$

The standard deviation of fitting is $\sigma = 0.86$ and the correlation coefficient between the observed ($\ln T_a$) and fitted values is $r = 0.18$ (at the 99 % confidence level), slightly higher than that ($r = 0.078$) between T_a and f.

Figure 1 clearly shows that the above relationship is very loose (Kay et al. 2003) with great random errors. Such a relationship can not represent the intrinsic feature of solar flares. Therefore, we employ the averages of the flare parameters (T_a, T_d, T and E) over subclass (B1.0, B1.1, ..., C1.0, ..., M1.0, ..., X1.0, X1.1, ..., S2.8) to analyze the underlying relationships between them and f.

4 Relationships between the peak flux and temporal parameters since 1997

First, we employ the recent data since January 1997 as the integrated flux is available since then only. Figure 2 plots the averaged rise time (T_a, solid line in red), decay time (T_d, dotted line in green), event duration (T, dashed line in blue) and integrated flux (E, dash-dotted line in purple, right-hand scaled) as a function of the peak flux (f) in the logarithmic scale. The flare class is also shown at the bottom of the figure for comparison.

One can apparently see in Fig. 2 that, apart from a few data points of high-class flares due to the little records of events, most of them are close to the straight lines (in black) fitted by the following linear equation:

$$y = c + \tau \ln f, \tag{3}$$

$y \in \{T_a, T_d, T\}$, or

$$f = e^{(y-c)/\tau}. \tag{4}$$

Specifically, for T_a, T_d and T,

$$f = \begin{cases} e^{(T_a - 9.1 \pm 0.8)/(2.4 \pm 0.2)}, \\ e^{(T_d - 8.8 \pm 0.3)/(1.0 \pm 0.1)}, \\ e^{(T - 17.9 \pm 1.0)/(3.4 \pm 0.3)}, \end{cases} \tag{5}$$

where $\pm$ represents the 1-σ deviation. The standard deviations of fitting are $\sigma = 10.5$, 4.3 and 12.6 (or 1.7, 1.5 and 3.0 if using the 'not-too-little' records of $\leq$ M4) minutes for $y = T_a$, T_d and T, respectively.

For the averaged integrated flux (E), which can be estimated as the average energy released by the flare, $y = \ln E$ and $x = \ln f$, we obtain $E = e^{6.69 \pm 0.03} f^{1.043 \pm 0.008}$, or

$$E = (807 \pm 21) f^{1.043 \pm 0.008}. \tag{6}$$

This equation is close to that ($E \propto f^{1.10}$) found by Veronig et al. (2002) using the non-averaged quantities.

If the rise time T_a is viewed as a stochastic quantity (as it is), the first formula in Eq. (5) suggests that the flare flux increases with time in the form of

$$f(t) = e^{(t-9.1)/2.4}, \tag{7}$$

or, in general,

$$f(t) = e^{(t-c)/\tau}. \tag{8}$$

It represents the average temporal variation (profile) of the flux at the rising phase of flaring.

(a) At $t = 0$, $f(0) = 0.021$, indicating that the flare events were recorded above the A2.1 level on average, close to the noise level $f_{\text{noise}} = A2.0$ (Feldman et al. 1997; Aschwanden and Freeland 2012).
(b) For a B1.0 flare ($f = 0.1$ μW/m^2), $t_{B1} = 9.1 + 2.4 \times \ln 0.1 = 3.7$ (minutes), implying that the average rise time of B1.0 flares (3.7 minutes) is slightly longer than the threshold of 3 minutes when a flare is recorded (Veronig et al. 2002).
(c) The second formula of Eq. (5) suggests that a longer decay time (T_d) tends to be associated with a higher peak flux (f). It represents the average temporal variation (profile) of f at the decaying phase of flaring:

$$f(t) = e^{(t' - 8.8)/1.0}, \tag{9}$$

where t' is calculated backwardly from the end of flare. If using the time t ($= T_d - t'$) calculated forwardly from

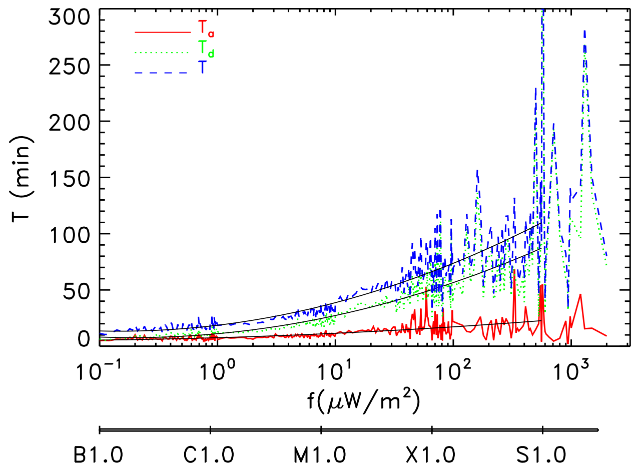

Fig. 3 Averaged rise time (T_a, *solid line in red*), decay time (T_d, *dotted line in green*) and event duration (T, *dashed line in blue*) of *SXR* flares as a function of the peak flux (f) prior to 1997

the peak time, the temporal variation of f at the decaying phase of flaring would be in the form of

$$f(t) \propto e^{-t/1.0}. \tag{10}$$

(d) From Eq. (8), one obtains

$$df/dt \propto f, \tag{11}$$

or

$$dE/dt \propto E \tag{12}$$

by combining Eq. (6). This relationship seems to be consistent with and to support the hypotheses of the RV model (Rosner and Vaiana 1978) that flaring is a stochastic process and that the e-folding time ($\frac{E}{dE/dt}$) for energy storage is constant. However, in the RV model, E refers to the total energy: $E_T = E_0 + E$, where E_0 (constant) is the internal energy of the flare system and E the energy supplied by the external forces straining the flaring volume that will be eventually liberated during the flare (Rosner and Vaiana 1978). This implies that the energy added by the external forces is assumed to be proportional to the total internal energy of the system (Bradt et al. 1975). While in Eq. (12), E refers only to the flare energy.

5 Relationships between the peak flux and temporal parameters prior to 1997

Now, we examine the above relationships using the data prior to 1997 (from 1975 to 1996), as shown in Fig. 3 for the averaged T_a (solid line in red), T_d (dotted line in green) and T (dashed line in blue) over subclass (B1.0, B1.1, ..., S2.8) as a function of f.

In Fig. 3, the rise time (T_a) seems to also follow a straight line fitted by Eq. (3), or

$$f(t) = e^{(T_a - 7.7\pm0.5)/(2.0\pm0.2)} \tag{13}$$

with the standard deviation of $\sigma = 6.0$ (minutes) for T_a. As discussed in the above section, this equation implies that, at the rising phase of flaring, the flux varies with time in the form of

$$f(t) = e^{(t-7.7)/2.0}, \tag{14}$$

similar to the case when using the data since 1997.

However, the decay time (T_d) and duration (T) skew upwardly and depart from the possible straight lines fitted by Eq. (3). Instead, they are better fitted by a quadratic polynomial:

$$y = a + b \ln f + \tau (\ln f)^2. \tag{15}$$

Since there are much fluctuations for high-class flares due to the little number of records (for example, there is only one X5.7-class flare event with $T_d = 473$ and $T = 528$), we fit them to the quadratic polynomial using only the data of $\leq$ X5.6. The fitted parameters (a, b and τ) are listed in Table 1. The standard deviations of fitting are $\sigma = 5.9$, 14.1 and 15.9 (or 1.6, 2.9 and 3.9 if using the 'not-too-little' records of $\leq$ M4) minutes for $y = T_a$, T_d and T, respectively.

A reasonable solution to Eq. (15) is

$$\ln f = \sqrt{\left(y - a + \frac{b^2}{4\tau}\right)/\tau} - \frac{b}{2\tau}, \tag{16}$$

or

$$f = e^{\sqrt{(y-t_0)/\tau} - c}, \tag{17}$$

where

$$\begin{cases} t_0 = a - b^2/(4\tau), \\ c = b/(2\tau). \end{cases} \tag{18}$$

Therefore,

$$f = \begin{cases} e^{\sqrt{(T_a-5.0)/0.17}-3.8} & \text{(for rise time)}, \\ e^{\sqrt{(T_d-7.6)/1.24}-1.7} & \text{(for decay time)}, \\ e^{\sqrt{(T-13.3)/1.41}-1.9} & \text{(for duration)}. \end{cases} \tag{19}$$

Table 1 The fitted parameters by the quadratic function (15) using the data prior to 1997

y	a	b	τ	σ
T_a	7.5 ± 0.5	1.3 ± 0.3	0.17 ± 0.07	5.9
T_d	11.1 ± 1.1	4.1 ± 0.8	1.24 ± 0.17	14.1
T	18.6 ± 1.2	5.5 ± 0.9	1.41 ± 0.19	15.9

If flaring is again assumed to be a stochastic process, Eq. (17) suggests that the flare flux at the rising phase varies with time in the form of

$$f = e^{\sqrt{(t-t_0)/\tau}-c}, \tag{20}$$

or

$$df/dt \propto \frac{f}{\sqrt{t-t_0}}. \tag{21}$$

This result is different from that (Eq. (11)) when using the recent data since 1997 and inconsistent with the hypothesis of the RV model (Rosner and Vaiana 1978) that the temporal rate of flare energy is proportional to the energy (Eq. (12)).

5.1 A Stochastic-Diffusive model

In order to explain the power law distribution of solar flare energy, Rosner and Vaiana (1978) proposed an energy-storage model by assuming that flaring is a stochastic relaxation phenomenon and that the e-folding time for energy storage is constant, as described by Eq. (12), or

$$dE/dt/E = \alpha. \tag{22}$$

In the present study, this means that the energy added by the action of external forces (dE) during the time interval $[t, t+dt]$ is assumed to be proportional to the total energy already stored in the flare system.

In fact, the 'constant' α (storing rate) may not always be the same since it is likely related to the convective turbulence (Rosner and Vaiana 1978; Parker 1988; Lu and Hamilton 1991). The turbulent heating rate is inversely proportional to the effective correlation length (Cranmer 2009). The size of propagation for a diffusion process obeys approximately the diffusive scaling law (Aschwanden 2012),

$$x(t) \propto \sqrt{t}, \tag{23}$$

Therefore, by combing the above facts, if α is assumed to be inversely proportional to the size scale of diffusion after some relaxation time t_0,

$$\alpha \propto 1/x(t-t_0) \propto \frac{1}{\sqrt{t-t_0}}, \tag{24}$$

Eq. (22) becomes

$$\frac{dE}{E} = \frac{1}{2\sqrt{\tau}} \frac{dt}{\sqrt{t-t_0}}, \tag{25}$$

where

$$A = \frac{1}{2\sqrt{\tau}} \tag{26}$$

is the proportion constant. The solution to this equation is

$$E(t) = e^{\sqrt{(t-t_0)/\tau}-c}, \tag{27}$$

with c being an integral constant. After using the power-law relationship between f and E (Eq. (6)), Eq. (25) becomes Eq. (21) and its solution is just Eq. (20) except for a proportion coefficient. This equation represents the energy storage (heating) process at the rising phase of flaring.

Similarly, this analysis can also be applied to the decaying phase of flaring (Eq. (19)) if t is viewed as the time calculated backwardly from the end of flare as discussed in Sect. 4 (replacing t by $t' = T_d - t$). But the decaying process is slower than the rising process as $\tau_d > \tau_a$.

6 Discussions and conclusions

Studying the temporal variation of flare intensity would help in understanding the energy storage/release process of flaring and the heating mechanism to the corona. In order to better understand the process of flaring, we analyzed the systematic relationships of the rise time (T_a), decay time (T_d) and duration (T) of the flare event with the peak flux (f), by using the averaged parameters over subclass. Because if using the original data, the relationships between f and the temporal parameters ($y \in \{T_a, T_d, T\}$) are very loose (Fig. 1) due to random errors (Pearce and Harrison 1988; Parker 1988; Kay et al. 2003) that may submerge the possible systematic relationships to some extent. From a physical point of view, each peak flux should be accompanied by an intrinsic life (close to the average). The temporal variation in f reflects the energy storage/release rate of flaring. The above relationships show different behaviors before and after 1997. After 1997, the temporal parameters vary linearly with $\ln f$, in consistent with the statistical hypothesis of the RV model (Rosner and Vaiana 1978). However, before 1997, they appeared much different behaviors, especially for the decay time (T_d) and duration (T) that depart from the linear relationships of $\ln f$ and are better fitted by a quadratic polynomial. This implies that the energy storage/release process of flares before 1997 showed some differences from that after 1997. A Stochastic-Diffusive model is therefore proposed in order to explain such phenomena by assuming that the storing rate (α) is inversely proportional to the size scale of diffusion and by combing the diffusive scaling law.

One may argue that the reported *SXR* flare times prior to 1997 were derived from the Hα events if available (Veronig et al. 2002), which may result in discrepancies between the data prior to and since 1997. Even so, this does not affect the previous conclusions as we used the same standards of observation separately since and prior to 1997—the fitted parameters might change a little at most. As for the data set since 1997, considering the fact that the end time of a flare is determined when the flux is equal to half of the 'peak', the decay time of a higher-class flare is more underestimated than a lower one (Aschwanden 2012). If so, the curves about the temporal parameters (T_d and T) in Fig. 2 should skew more upwardly at higher values, which in turn leads to the result more or less approaching to that using the dada prior to 1997 (diffusive model).

In the wave (alternating current) heating mechanism, convective flows interacting with magnetic flux elements in the photosphere can produce magnetohydrodynamic (MHD) waves that propagate up and dissipate their energy in the corona (Alfvén 1947). In the reconnection (direct current) heating mechanism, the random motions of photospheric footpoints can result in twisting and braiding of coronal field lines and form thin current sheets in the corona within which magnetic reconnection can cause impulsive heating events (Parker 1988). The observed X-ray emission is in fact the cumulative effect of many different coronal heating processes such as above (van Ballegooijen et al. 2011).

Since the flux tubes are highly turbulent due to the convective downflows (Cattaneo et al. 2003), the above processes are all related to the turbulence. For example, the motions of the photospheric footpoints of the magnetic field lines can excite MHD and Alfvén waves in the magnetic loops (Ruderman et al. 1997), and generate turbulence via nonlinear wave–wave interactions (van Ballegooijen et al. 2011). Rappazzo et al. (2008) pointed out that the dynamics of a flux tube with its footpoints stirred by random motions is in fact an MHD turbulence problem. The turbulence in the coronal loops may play a very important role in coronal heating (Nakariakov et al. 1999; van Ballegooijen et al. 2011).

In the present study, we have not specified that the corona is heated whether by waves or by current sheets. We examined systematically the temporal variation (profile) in the peak flux of flare as a whole. The flare energy comes from the synthesized effect of different heating processes. In some cases, one heating mechanism may be dominant, while in other cases, another mechanism may prevail. The temporal profile of the peak flux represents the energy storage/release rate of flaring that is related to the turbulence. The result in the present study shows that the flare energy added by the external source depends not only on the total energy already stored in the flare system but also on the convective turbulence or the external magnetic enurement. In the original RV model (Eq. (22)), the storing rate (α) is simply assumed to be a constant unrelated to the turbulence. Under a certain external magnetic condition, the flaring process can be well described by the RV model. Under another different external magnetic enurement, the storing rate (α) may be different (Eq. (24)), reflecting the variation in the external magnetic enurement via turbulence. Thus, the Stochastic-Diffusive model (Eq. (25)) may be viewed as a modified RV model after considering the external enurement (turbulence). In addition, the energy storage process of flaring may not be an instantaneous phenomenon. The flare energy at a ceratin time is the integrated effect of different processes in the past (Du 2011a, 2012a; Du and Wang 2012). Therefore, the energy release process of flaring has some relaxation (or delay) time relative to the source supplying the energy. Certainly, the time response may be another rather complicated problem need to be further carefully studied in future.

It is well known that the solar activity (as indicated by sunspot numbers) becomes weaker in the recent two cycles (Usoskin et al. 2007; Du 2011b, 2012b; Attia et al. 2013; Zhdankin et al. 2014). In addition, the average solar polar field strength changed its behavior from increase to decrease around 1997[2] (Rušin et al. 2014). The variation in the magnetic fields may change the turbulence in the corona (Cranmer 2009; Zhdankin et al. 2014) and may eventually change the heating rate of flaring. Prior to about 1997, due to the stronger magnetic field, the storing rate (α) may be related to the turbulence. Thus, the temporal variation of the flare energy is like that expressed by Eq. (27). After about 1997, due to the weakening magnetic field and turbulence, the storing rate (α) may have little change, so that the temporal variation of the flare energy obeys the RV model (Eq. (12)). To summarize, the process of flaring should obey the above stochastic-diffusive model (Eq. (25)). The different behaviors of the relationships between the peak flux and temporal parameters since and prior to about 1997 may be likely related to the variation in the turbulence in the corona caused by the weakening magnetic field activity in the recent two decades.

Acknowledgements We thank the anonymous referee for constructive comments. This work is supported by the National Natural Science Foundation of China (NSFC) through grant 11473040 and the National Basic Research Program of China through grant Nos. 2012CB957801 and 2011CB811406.

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