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A new and quantitative prediction scheme for solar flares

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ABSTRACT

At the present time, there is no quantitative way to predict not only the onset time of solar flares, but also their intensity. In the past, most solar flare prediction studies have searched for various precursors of the onset of flares. In this paper, we consider a new and quantitative approach to predict the onset of the explosive process of solar flares and their intensity, based on the principle that solar flares are basically various manifestations of electromagnetic energy dissipation, so that a dynamo process in the photosphere as its power supply is essential. The power is a basic physical quantity (erg/s), so that it can, at least in principle, be universally applicable for all flares. The power of the photospheric dynamo is given by the Poynting flux $P= V(B^2/8\pi)S$ erg/s, where V and B are the plasma speed and magnetic field intensity, and S is the dimension of the plasma flow; these quantities are in principle *observable simultaneously all together*, in addition to the dissipation rate δ (for example, the Hα emission rate). In fact, if one can follow the development of the power P(t) and $[\int P(t)dt - \int \delta(t)dt]$, it may be possible, together with various precursors, to predict in principle the onset time and the intensity of flares at least semi-quantitatively, although this task will require much experience on the basis of a large number of flares. Unfortunately, however, all the needed simultaneous data set (V, B, S, δ) is not available in the present literature, so that one incomplete case is examined. This concept has been examined for auroral substorms, which are also manifestations of electromagnetic energy dissipation and have the explosive feature. This was possible, because the simultaneous data sets (V, B, S, δ) are available.

1. Introduction

In predicting solar flares, the past efforts have mainly been to attempt to search for possible precursors or pre-flare conditions. Several examples are photospheric plasma motions (Martres et al., 1973; Zao, 2009), particular magnetic configurations, such as magnetic shear (Wang, Ewell and Zirin, 1994) and "sigmoids" (Canfield et al., 2000), a strong magnetic inversion (Steward et al., 2011), magnetic flux changes (Wang and Liu, 2010), imaging of magnetic field reconnection (Su et al., 2013), modeling (Fisher et al., 2015), electric field (Kazachenko et al., 2015). Unfortunately, most precursors are not necessarily always present and may not applicable for all flares.

Solar flare phenomena are various manifestations of electromagnetic energy dissipation processes. Therefore, they must be powered by a dynamo process. Unfortunately, this concept of dynamo process (in unit of erg/s) as its power supply has been lacking in most flare studies, except that both Brun et al. (2004) and Vogler and Schssler (2007) considered a dynamo process associated with convective motions in the upper layer of the sun and showed that the convective motion can generate a significant amount of magnetic energy.

This lack is because it has generally been presumed that magnetic energy in the form of an anti-parallel magnetic configuration in sunspots or coronal magnetic fields pre-exists, so that some of the main subjects have been to find anti-parallel magnetic field configurations for magnetic reconnection. Even one of the most extensive reviews on the subject, Shibata and Magara (2011) mentioned only the availability of magnetic energy in terms of $B = 1000$G "in a typical sunspot".

In this paper, a new scheme is proposed by considering a photospheric dynamo process as the power supply for solar flares. The power is one of the basic physical quantities (erg/s) and thus should, at least in principle, be applicable for all flares. Since all the quantities needed for estimating the dynamo power P (the plasma velocity V, magnetic field intensity B, dimension of interaction S, as well as the dissipation rate δ) are simultaneously observable, it is worthwhile to try to test the proposed *quantitative* scheme. This concept is examined for auroral substorms, which have also the explosive feature. In this paper, we deal with local dynamo processes in active regions in the photosphere, not the global dynamo process deep in the interior of the sun.

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2. Dynamo power and the two components of dissipation (DD,UL)

2.1. Photospheric dynamo

Since solar flares are mostly various manifestations of electromagnetic processes, a dynamo as the power supply is essential. The dynamo power is defined by the Poynting flux P (erg/s) in terms of *observable* quantities (cf. Akasofu, 2017a) and is given by:

$$P = \int \boldsymbol{E} \times \boldsymbol{B} \bullet \boldsymbol{dS} = V(B^2/8\pi)S,$$

where V and B are the speed of photospheric plasma flow and magnetic field intensity and S is the dimension of plasma flows; it is given by $S = L \times d$, where L is a lateral dimension of photospheric plasma flow and d the depth of the photosphere involved in the dynamo process (the longitudinal dimension = the speed of plasma × duration of flares); for simplicity, $\boldsymbol{V}$ is assumed to be perpendicular to $\boldsymbol{B}$ in the photosphere. The corresponding dissipation rate (erg/s) is denoted by δ (as a first approximation, the Hα emission rate). Welsch et at. (2009) and Fan et al. (2011) examined specific solar flares in terms of the Poynting flux, but they did not consider its application in predicting the occurrence of flares. Their works will be discussed in Section 3.1.

2.2. Auroral substorms

In studying the power-dissipation relationship, it is worthwhile to review studies auroral substorms, which consist of the growth, expansion and recovery phases. Like solar flares, they are also manifestations of electromagnetic energy dissipation, in spite of the fact that there is at least 10^8 difference in the power and energy between them. Solar flares and auroral substorms have various morphological similarities. Both phenomena have an explosive feature (the expansion phase for auroral substorms), so that the energy for the explosive component must be accumulated before the released (unloaded) rapidly for the explosive process to occur.

In fact, both phenomena have been discussed almost exclusively in terms of anti-parallel magnetic field configurations and magnetic reconnection, although we consider a different view on both phenomena in Section 3.2.

The accumulation of magnetic energy for the explosive process (the expansion phase) must be supplied by a dynamo, the solar wind-magnetosphere dynamo (and a photospheric dynamo for solar flares). For auroral substorms, V and B are the solar wind speed and the intensity of magnetic field of the interplanetary magnetic field (IMF) respectively, and $S = \sin^4(\theta/2)l^2$ where θ is the polar angle of the IMF and l is 5 Re (Re = the earth's radius); the dissipation rate δ is mainly the Joule heat production rate in the polar ionosphere; note that in the past, the power has been observationally discussed in terms of ε= ($P/8\pi$); for details of this subject, see Akasofu (2017b).

Since auroral substorms must be driven by the solar wind-magnetosphere dynamo, they should have the directly driven (DD) component by the dynamo and also the unloading (UL) component, which results from the accumulated energy, representing the explosive feature (the expansion phase). This is also the case for solar flares, as we discuss in Section 3.

Thus, in order to study the explosive process of auroral substorms, the UL component is separated from observed data (DD + UL). Since P(t) and δ(t) are available for auroral substorms, the separation of the DD and UL component is made in terms of the electric current intensity in the ionosphere (cf. Akasofu, 2017b). The results are shown in Fig. 1, although it is only a first approximation result. It can be seen that the directly driven DD(t) component follows roughly the power ε(t), while UL(t) component is impulsive, being independent of the power ε. In auroral substorms, the accumulation of magnetic energy occurs during the growth phase, because the conductivity of the ionosphere is too low to dissipate the power as the Joule heat before the expansion phase onset. On the other hand, the accumulation does not occurs after the brief expansion phase, because the ionospheric conductivity becomes high enough to dissipate the power even if the power is high enough. This point will be mentioned again in Section 3.3 for solar flares.

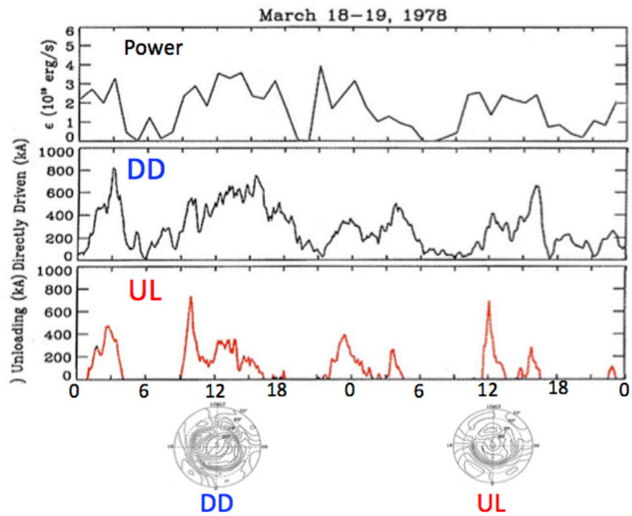

Fig. 1. From the top, the power (ε = $P/8\pi$), the directly driven (DD) and the unloading (UL) components. Both DD and UL currents in the ionosphere are also shown (Akasofu, 2017b).

All the quantities on auroral substorms relevant to solar flares will be mentioned in association with the corresponding solar quantities Section 3.1.

3. Solar flares

Since solar flares are powered by the photospheric dynamo, there should be two components of dissipation. The first component is the directly driven (DD) component (δ_{DD}), which is directly driven by the dynamo process. The second is the unloading (UL) component δ_{UL}(t), which results from unloading (releasing) of the accumulated magnetic energy for the explosive process.

3.1. Directly driven (DD) component

Actually, the need for a photospheric dynamo was already *implicitly* mentioned in the very first study of solar flares on the basis of magnetic reconnection. Sweet (1958) proposed that two approaching sunspot pairs produce an anti-parallel magnetic configuration. It is *his hypothetical motion of sunspot pairs, which constitutes a photospheric dynamo process*. In fact, Akasofu (2017a) showed that a photospheric dynamo can supply the minimum power for 2.8×10^{26} erg/s (=10^{30} erg ÷ one hour), for modest values of V, B, S (= L and d) values; V = 1 km/s, B = 100G, $L = 5 \times 10^4$ km, d. = 1 000 km; it is generally considered that the energy associated with weakest flares is 10^{30} ergs. The so-called 'emerging spot' (a collision of two spots) model (Heyvaerts el al. (1977) may also be considered as a dynamo process produced by a similar interaction between emerging spots and old spots.

Choe and Lee (1996a,b) showed how their photospheric dynamo works along the neutral line under a magnetic arcade (Fig. 2a and b). Their model assumes an anti-parallel plasma flow (V = 2 km/s) along the centerline of arcade, which is the boundary (the neutral line) of two *unipolar regions* of opposite polarity, and magnetic field intensity B = 12 G (= 6 G + 6 G). These values are well within the observational constraints along the neutral line between two unipolar magnetic regions. It is well-established that solar flares tend to occur along the neutral line even within a very complex sunspot group. In an active sunspot group, flares