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Energy and Mass Supply in the Decay Phase of Long Duration Solar Flare Events

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ABSTRACT

A new mechanism is proposed to supply energy and mass in the decay phase of long duration solar flare events (LDEs). LDEs are known to be caused by filament eruptions and bright arcade structures continue for several hours or even a day. To overcome the short cooling time, continuous energy and mass supply is required. Continuous magnetic reconnection in the current sheet extended above the arcade has been proposed to supply energy and mass. However, no direct observations of the current sheet have been reported. The new mechanism that we are proposing is based on the recent observations of down flows onto the top of arcades along the vertical spiky features observed by *Yohkoh* Soft X-ray Telescope. We interpret these down flows as free-falling plasma. Falling plasma from high altitude can convert its potential energy into thermal energy and heat itself with an average temperature of several million-degree Kelvin. Observations show that the down flows continue for several hours. Coronagraph observations by SOHO/LASCO also show many falling features after coronal mass ejections. We propose these falling plasmas as the cause of the energy and mass supply for LDE events in the long lasting decay phase instead of magnetic reconnection.

Subject headings: Sun: flares, Sun: corona

1. Introduction

Long duration solar flare events (LDEs) are known to be closely related to coronal mass ejections (CMEs) into the interplanetary space (Kahler 1992). These mass ejections are also closely related to filament eruptions. Filaments are located along magnetic polarity reversal lines. Above the filament, an arcade of magnetic loops connects the opposite polarity regions. By the eruption of the filaments, dense plasma in the filament is lifted into the higher corona and becomes part of CMEs, and the overlying arcade of loops gets brighter in soft X-ray. This bright arcade of loops lasts for a long time and is called as LDE.

It is known that the temperature in the decay phase of LDEs is very stable even though the emission measure drops one or two order of magnitude. Smith et al. (1994) observed a LDE flare and determined the temperature using the Ca line ratio. They showed that during 7 hours of the decaying phase, temperature dropped only 0.3×10^6 K from 8.4×10^6 K. Schmieder et al. (1996) and Harra-Murnion et al. (1998) also got the similar results using different methods.

This group of solar flares has been explained by open-up and re-closing of the arcade of magnetic field. This is the standard reconnection model of solar flares at present (e.g. Golub and Pasachoff (1997)). Erupting filaments opens up the overlying magnetic arcade and create oppositely directed magnetic fields separated by a current sheet. These magnetic fields reconnect due to a localized anomalous resistivity. Due to the reconnection, the stored energy in the current sheet is released and the mass in the current sheet is supplied to the top of the arcade. Continuous inflow into the current sheet explains long duration of the events.

Recently, Shibasaki (2001) proposed a quite different scenario based on the high-beta plasma disruption. When the ascending prominence hit the overlying arcade of loops, prominence plasma interchanges with the overlying arcade through the ballooning instability. This instability corresponds to the initial and the main phase of solar flares. Prominence plasma is accelerated by the instability process in the form of "ballooning fingers". Each finger further extends into higher corona and eventually reaches into the interplanetary space. Spiky structures, or rays, found by *Yohkoh* Soft X-ray Telescope (Švestka et al. 1998) correspond to these fingers. It is also found that the downward-moving dark voids continues for hours along the rays above the arcade (McKenzie et al. 1999; McKenzie 2000).

In this letter, we interpret these dark voids as cool and dense plasma and propose to use the falling plasma as the source of energy and mass in the decay phase of LDEs lasting for long time even a day after the eruption. The idea of using the potential energy of erupted prominences to heat H_α flares was first proposed by Hyder (1967). He tried to explain H_α flare ribbons by prominence plasmas sliding down from the top of the supporting arcades to the chromosphere. Here, we propose to use the potential energy of the prominence plasmas lifted high into the corona or even into the interplanetary space. In Section 2, recent observational evidences are surveyed and the new idea is explained in detail. Also, we discuss on the possibility to apply this mechanism to more general coronal heating. Conclusions and

Discussions are given in Section 3.

2. Observational Evidences and the Proposed Heating Mechanism

2.1. Fan of Rays and Plasma Down Flow

Soft X-ray imaging observations of long duration events (LDEs) near the limb by *Yohkoh* satellite showed rays extending from the top of the flare arcades (Švestka et al. 1998). The rays form a fan structure. Švestka et al. (1998) also found that these rays are channels to feed plasma into interplanetary space. The fans of rays can continue for several days after the LDE events. McKenzie et al. (1999) found down flows near arcade tops along the rays during the decay phase of a LDE event. The authors interpreted these dark blobs moving downwards as the shrinking flux tubes linking the current sheet. McKenzie (2000) searched for the similar events and found 22 events with fans of rays during the period of 16 months. Among them, 12 events are associated with down flows in the region immediately above the flare arcade. The projected down flow speeds are 45 - 500 km s^{-1}, and they never exceed the free-fall velocity from infinity. He concluded that the speeds of down flows are consistent with either gravitational free-fall or magnetic field line shrinkage. He also concluded that no direct evidence was found to support the idea of cool material falling back to the surface of the Sun from the CME. However, he also mentioned that available EUV images are of insufficient cadence to rule out completely the infalling cool materials. He suggested observations with higher cadence and with more complete temperature coverage. Here we assume that the downward moving dark blobs as cool material falling back to the surface of the Sun from the CME.

2.2. Coronal Inflows

Recently, down flows in the higher corona were discovered by the SOHO/LASCO coronagraph (Wang et al. 1999). The detected down flows are in the range of 1 - 3 solar radii from the surface. The lower limit is by the occultation disk of the coronagraph. The down flows are of small-scale structures and the velocity is 20 - 100 km s^{-1}. They were typically observed 12 - 36 hours after the onset of a CME. Many had a cusp-like appearance. Further studies by Sheeley et al. (2001a) and Sheeley et al. (2001b) show that the occurrence rate of inflows is 10 - 20 per day in average. Detected numbers seems to be highly dependent on the contrast between the down flow features and the background. They suggested that some inflow events may represent the retraction of closed loops that have been stretched to a maximum height.

2.3. Energy and Mass Supply to the LDE

By combining these newly discovered evidences, we assume that the plasma lifted by prominence eruptions reaches into the higher corona and returned onto the arcade top. They are guided by the magnetic line of force that were pulled out from the top of the arcade as the ballooning fingers in the process of eruption. Cusp-like appearances of the down flows correspond to the fingertips. They are seen as rays above the arcade of loops in LDE flares. The falling mass is fed around the top of the arcade and releases its potential energy as thermal energy. The potential energy difference of the plasma cloud with mass m located at a certain height, and that located on the solar surface is equal to the kinetic energy (K) gained after the free fall. It is:

$$K = mg_0R_0\frac{h}{h+1}, \tag{1}$$

where h is the height from the surface normalized by the solar radius (R_0) and g_0 is the surface gravity. This energy is converted to the thermal energy when it enters into the dense atmosphere or when the free-fall velocity exceeds the local sound velocity. Non-thermal processes are expected when the kinetic energy is converted to the thermal energy, such as shocks or turbulences. If the falling plasma heats by itself uniformly, the expected temperature increase is as follows assuming that the energy is equi-partitioned by three degrees of freedom of both protons and electrons:

$$T = \frac{m_pg_0R_0}{3k_B}\frac{h}{h+1}, \tag{2}$$

where m_p is the proton mass and k_B is the Boltzmann constant. For simplicity, we assumed fully ionized hydrogen gas in this calculation. If we express the temperature in the unit of 10^6 K as T_6:

$$T_6 = 7.7 \times \frac{h}{h+1}. \tag{3}$$

We should note that the temperature is independent of the amount of the falling plasma. If the falling plasma heat the surrounding plasma also, this value should be divided by the ratio of the heated plasma mass and the falling plasma mass. This temperature regulation mechanism of the post-flare arcade is very robust and can explain observational results, both the absolute value of the temperature and its stability.

It is not known from observations how much mass is falling, hence we cannot calculate the potential energy released during the decay phase. We try to estimate the energy with an assumption of a fraction of the falling mass relative to the total erupted mass. Average mass of prominence eruption is about 2×10^{15} g (Engvold 1980) and this mass is close to the total mass of CMEs (Wagner 1984). The potential energy of this mass at a large height is $\sim 4 \times 10^{30}$ erg. We assume that some fraction (f) of the whole mass turns to fall back onto the top of the arcade along the rays during the decay phase. If $f \sim 0.1$, the released potential energy is about 10 percent of the total energy of average flares (Švestka 1976). This amount of energy may be enough as the decay phase. The fraction f may differ from event to event.

The free-fall time t_0 is calculated as follows:

$$t_0 = \frac{R_0}{V_c}\sqrt{h+1}[\sqrt{h} + (h+1)arcsin(\sqrt{\frac{h}{h+1}})], \tag{4}$$

where V_c is the free-fall velocity at the surface from infinity:

$$V_c = \sqrt{2 g_0 R_0} \tag{5}$$

$$= 6.2 \times 10^7 \text{cm s}^{-1}. \tag{6}$$

In case of $h = 1$, t_0 is about one hour. It can be as long as one day if $h \sim 12$. We need to add the lifting time when we discuss the time after the eruption. Long duration of inflow features and also the long duration heating and mass supply for the LDE decay phase can thus be explained by the very simple mechanism.

2.4. Application to Coronal Heating

The heating and mass supply mechanism explained in the previous subsection can be applied to more general coronal heating. The idea of using potential energy to heat the corona was first proposed by Vand (1943) just after the establishment of the million degree corona. The idea was to use the interplanetary matter to heat the corona. But the mass is not enough to supply continuous heating of the corona. Hoyle (1949) proposed to use the interstellar matter to heat the solar corona. However, due to the discovery of the solar wind, this idea was forgotten. Recently, Hammer et al. (1993) proposed an idea to heat coronal hole, where magnetic field has an open structure, by releasing the potential energy of the plasma occasionally lifted up.

Inflows detected by coronagraph (SOHO/LASCO) (Wang et al. 1999) make it realistic to reconsider the possibility to heat the corona by potential energy. Sheeley et al. (2001a) noticed frequent inflows without CMEs. The inflows are very faint and difficult to detect. So, even the rate of the events that they counted was $10 \sim 20$ per day, the actual inflow events can be more frequent. However, no information is available about the mass from the current observations. Hence, we cannot determine the total available potential energy.

To keep the whole quiet Sun corona as a couple of million degrees, necessary energy per day is of the order of 10^{33} erg. To get this energy from the potential energy of the lifted mass, several hundreds of CMEs are necessary per day. But only one CME per day is detected in average (Wagner 1984). Very efficient mass lifting mechanism is necessary to apply this mechanism for coronal heating.

3. Conclusions and Discussions

Based on the recent discoveries of 1) down flows just above the flare arcades of LDEs along the ray structures and 2) down flows in the higher corona after CMEs, we proposed a new mechanism of energy and mass supply in the long decay phase. The energy and mass are supplied by the falling plasmas that were originally lifted as prominence eruptions. The falling plasmas are guided by the magnetic lines of forces connecting the erupted plasmas and the arcade top as the result of the ballooning process during the eruption. Long duration is explained by the free-fall time from high altitude. It can be as long as one day if the height is twelve times of the solar radius. The falling plasma temperature is regulated to be several million degrees if the falling plasma itself is uniformly heated by converting the free-fall kinetic energy that corresponds to the potential energy.

In the energy conversion process, from kinetic to thermal, non-thermal phenomena are expected such as shocks and turbulences. Smooth light curves of soft X-ray emission tell us that the energy release by each impact of plasma blobs are small compared to the total energy. Shocks and turbulences are favorable conditions for extended high-energy phenomena lasting several hours (Rank et al. 2001). Information about the falling mass is not available from the observations. Further studies are needed to measure the amount of falling mass. In this mechanism, the mass in the post flare loops is supplied from the corona directly, not by the evaporation from the chromosphere. This is consistent with the measurements of composition of flaring plasmas (e.g. Feldman (1996)). In this mechanism, flare energies should be contained in the lifting prominences. How the prominence stores the energy and why it is lifted are the main questions about LDE flares.

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