Article

Chinese Science Bulletin

Basic Plasma Processes in Solar-Terrestrial Activities

October 2011 Vol. 56 No. 1: 1–4
doi: 10.1007/s11434-011-****-*

Where do flare ribbons stop?

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Received August 31, 2011; accepted someday, 2011

The standard flare model, which was proposed based on observations and magnetohydrodynamic theory, can successfully explain many observational features of solar flares. However, this model is just a framework, with many details awaiting to be filled in, including how reconnection is triggered. In this paper, we address an unanswered question: where do flare ribbons stop? With the data analysis of the 2003 May 29 flare event, we tentatively confirmed our conjecture that flare ribbons finally stop at the intersection of separatrices with the solar surface. Once verified, such a conjecture can be used to predict the final size and even the lifetime of solar flares.

solar flares, magnetic field, separatrix

Citation: Chen P F, Su J T, Guo Y, and Deng Y Y. Where do flare ribbons stop? Chinese Sci Bull, 2011, submitted, doi: 10.1007/s11434-011-****-*

Because of the omnipresence of magnetic field in the solar atmosphere, the Sun presents a variety of activities, which are modulated with the 11-year solar cycles. One of the spectacular phenomena is solar flares. They represent the typical process that magnetic energy accumulated gradually in the corona is released rapidly and converted into thermal and kinetic energies. Morphologically, flares are classified into two types, i.e., compact and two-ribbon flares (e.g., [1]). Compact flares are characterized by a compact flaring loop, which does not show significant change in shape, whereas two-ribbon flares are characterized by flaring loop expansion and bright ribbon separation. Two-ribbon flares attracted more attention since they are frequently related to coronal mass ejections (CMEs).

To explain the appearance of the flaring loops, two ribbons, and their association with filament eruptions, a standard flare model was gradually developed by [2], [3], [4], and [5], which was later called CSHKP model. The standard flare model, where magnetic reconnection below an erupting flux rope is the key ingredient, was supported by a lot of observations, such as the discoveries of chromospheric evaporation, the cusp-shaped structure, the reconnection downflow, and inflow (see [6] for a review). However, it should be kept in mind that such a model is just a framework, and many detailed processes inside it await to be clarified and understood theoretically, for example, how the reconnection is triggered in the highly-conducting plasma. Another unclarified issue is related to the flare ribbon separation.

The characteristic feature of two-ribbon flares in Hα or any other chromospheric wavelength is the ribbon separation. The separating speed reaches up to 50 km s^{-1} in the impulsive phase and decreases to $\leqslant$ 1 km s^{-1} in the decay phase [7]. One important question remains to be answered is: where do the two ribbons finally stop? This paper is aimed to address such an issue.

1 Our conjecture

In the standard flare model, as a filament (or a magnetic flux rope in a general sense) erupts, all the overlying field lines are stretched up, leading to the formation of a current sheet below the flux rope. As reconnection is triggered and goes on in the current sheet, the reconnected field lines below the reconnection area, along with the heated plasmas, pile up. The

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previously-heated loops cool down due to radiation and heat conduction. Accelerated around the reconnection area, energetic particles, along with thermal conduction, are transferred down along the separatrix or quasi-separatrix layer (QSL) to heat the chromosphere, forming Hα ribbons and plasma evaporation. These processes result in the typical observed features of two-ribbon flares, i.e., the apparent expansion of the flaring loop and the separation motion of the flare ribbons (e.g., [8]). Such processes can keep going if the magnetic field lines straddling over the flux rope extend to a long distance in the horizontal direction, i.e., in the case of a large-scale bipolar field. However, at least two factors may terminate such an on-going reconnection process. One is that the reconnected field lines pile up to reach the reconnection area, which then hinders the anti-parallel field lines from further reconnecting. This factor can account for compact flares as demonstrated by [9], but not for two-ribbon flares, where the current sheet extends up well above the flaring loop. The second factor, which we propose to account for the limited lifetime of two-ribbon flares, is the existence of outer magnetic separatrices.

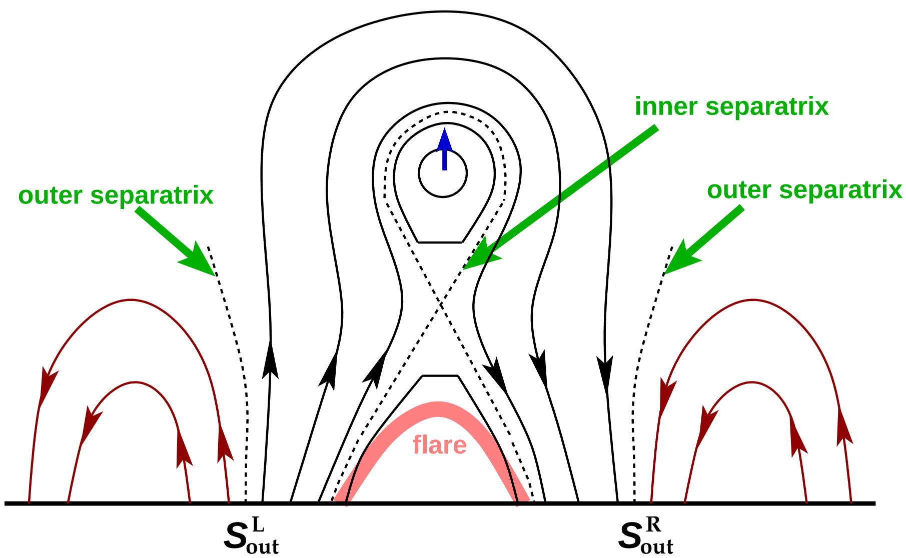

Figure 1 A sketch of magnetic reconnection model with both inner and outer separatrices being considered.

The idea is explained in Figure 1, the central part of which is essentially the same as the CSHKP model, i.e., a flux rope with a null point below resides inside a filament channel. An inner magnetic separatrix (*dashed line*) runs across the X-point. Note that in 3-dimensions the null point might be a singular line and the inner separatrix might be a QSL [10]. The difference of Figure 1 from the classical CSHKP model is that there exist two outer magnetic separatrix segments on the two sides of the filament channel respectively, as indicated by the dashed lines above S_{out}^{L} and S_{out}^{R}. Outside S_{out}^{L}–S_{out}^{R} the field lines belong to different flux systems, which can either be open field (i.e., a coronal hole) or closed field. As the flux rope erupts, only the field lines straddling over the flux rope between S_{out}^{L} and S_{out}^{R} can be stretched up and experience reconnection below the flux rope. This means that the moving flare ribbons will finally stop at the intersections of the outer magnetic separatrice with the solar surface, i.e., at S_{out}^{L} and S_{out}^{R}.

To confirm such a conjecture, we analyze the 2003 May 29 flare event, and study the spatial relation between magnetic separatrices and the final positions of the flare ribbons.

2 Observations and data analysis

On 2003 May 29, a GOES X1.2-class flare occurred at S06W37 in the active region AR10365. The flare started at ~00:51 UT and peaked at 01:05 UT. UV ribbons were almost invisible after ~02:00 UT. It was a typical long-duration event, showing two ribbons separating gradually. The flare loops and ribbons were well observed by the Transition Region and Coronal Explorer (*TRACE*, [11]) with a high spatial resolution of 1″ and a cadence of ~3 min. The photospheric vector magnetograms across the flare were obtained in Huairou Solar Observing Station (*HSOS*, [12]) with a pixel size of 0.35″ and a cadence of ~10 min. The coalignment of the two datasets is accomplished with the help of the magnetogram Michelson Doppler Imager (MDI) aboard the *Solar and Heliospheric Observatory* (*SOHO*).

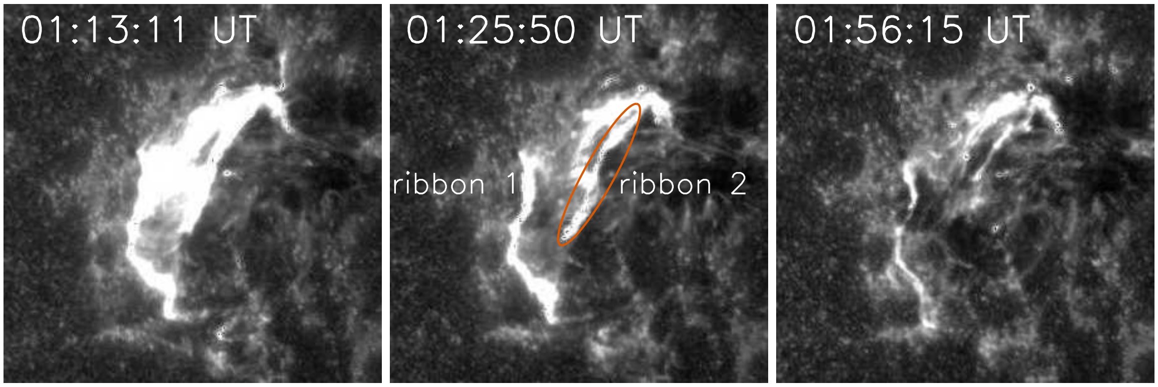

Figure 2 Evolution of the 2003 May 29 solar flare in the *TRACE* 1600 Å wavelength showing the separation of two ribbons. North is up. The ribbons 1 and 2 are marked, and it is noted a bright patch to the north of ribbon 2 persisted during the flare.

Figure 2 depicts the evolution of the flare in *TRACE* 1600 Å, where two ribbons were observed to separate slowly. Ribbon 1 is seperate from any other brightenings, whereas ribbon 2, marked by an ellipse, is connected to a bright patch in the north. At 01:56:15 UT, the flare ribbons nearly approached their final positions before fading away. Note that the bright patch to the north of ribbon 2 persisted during the flare, whose nature is beyond the scope of this paper.

The coronal magnetic field is extrapolated from the *HSOS* vector magnetogram before the flare peak, at 00:59 UT, with the non-linear force-free model [13]. Figure 3 illustrates the extrapolated coronal magnetic field lines with the photospheric vector magnetogram being rendered at the bottom. The different magnetic flux systems are clearly identified, and the boundaries between neighboring flux systems correspond to magnetic separatrices, across which field lines go divergently. The two separatrices related to the flare are indicated by two white arrows, which resemble the two flaring ribbons quite well.

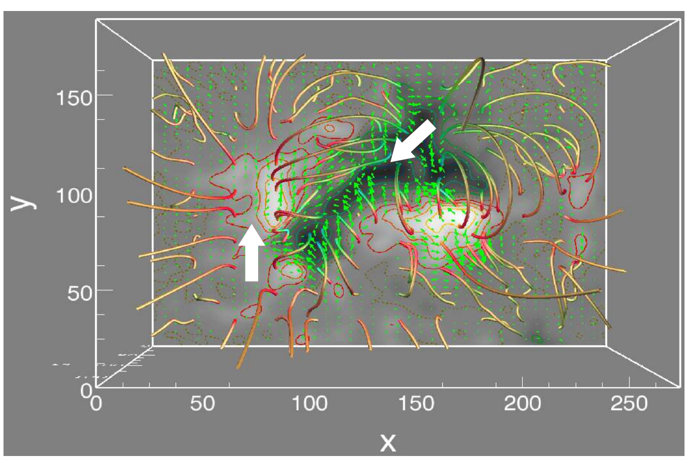

Figure 3 Top view of the extrapolated coronal magnetic field (*solid lines*) that is anchored to the photospheric magnetograms (*gray-scale* for the longitudinal component, and *arrows* for the horizontal components). The two white arrows indicate two separatrices.

In order to compare the locations of the separatrices with those of the two ribbons more quantitatively, we calculate the squashing degree Q, which characterizes the magnetic connectivity, with $Q >> 2$ corresponding to a QSL. Q is infinite at separatrices in theory, and is a very large value due to finite size of the numerical grid. The Q-map (*yellow lines*) is superimposed over the *TRACE* 1600 Å intensity map at 01:56:15 UT in Figure 4. It can be seen that ribbon 2 near the end of the flare is almost exactly cospatial with the intersection of the magnetic separatrix at the solar surface. Although ribbon 1 is also roughly cospatial with the intersection of the magnetic separatrix, it is inclined with the separatrix intersection with an angle of 20°.

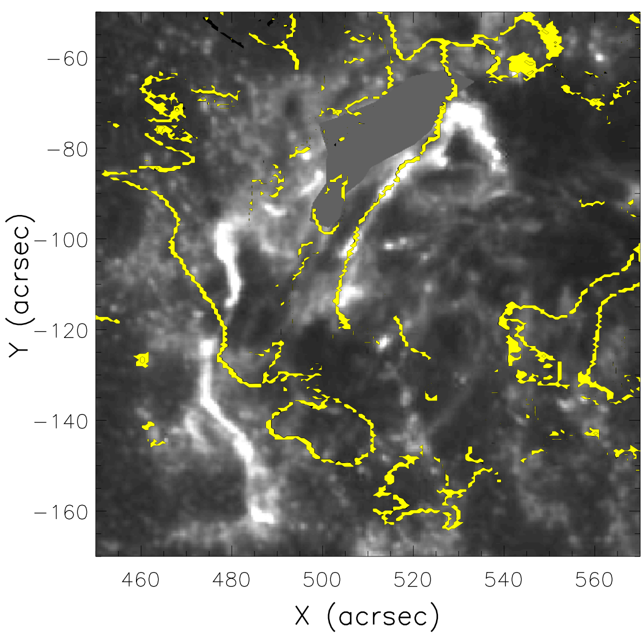

Figure 4 Comparison between the final locations of the flare ribbons at 01:56:15 UT (*gray-scale*) with the Q-map (*yellow lines*) at 00:59 UT, which indicates that the final location of ribbon 2 is cospatial with the footpoints of a magnetic separatrix and that of ribbon 1 is roughly cospatial with the footpoints of separatrix. North is up. Note that the bright patch to the north of ribbon 2 is removed.

3 Discussions

Magnetic separatrices and QSLs play an important role in active region heating [14] and magnetic reconnection as well

[15, 16]. Solar flares, either compact or two-ribbon flares, are widely explained in terms of magnetic reconnection [17]. In the reconnection model, magnetic separatrices (or QSLs in a more general sense) divide the reconnected field lines from the pre-reconnected field lines. Energetic particles and heat conduction are transported down to evaporate the chromospheric plasma to form flare loops. As the reconnection goes on, the flaring loop expands apparently, with its two footpoints (two ribbons in 3-dimensions) separating continually. According to such a reconnection model, at any time during a flare, the flare ribbons, i.e., the footpoints of the flare loops, are located at the intersection of inner magnetic separatrix (or QSL) with the solar surface, as illustrated by Figure 1. As the reconnection proceeds, this inner separatrix (or QSL) moves outward horizontally along with the flare ribbons. With this paper, we point out that there should also exist outer separatrices which border the filament channel, as marked by S^L_{out} and S^R_{out} in Figure 1. When all the field lines between the inner separatrices (or QSLs) and the outer separatrices have reconnected, no more field lines are available for further reconnection, and magnetic reconnection is expected to halt. When this happens, the flare ribbons reach the outer separatrices. In this paper, we analyzed the 2003 May 29 flare event. It is found that the final location of ribbon 2 well matches the separatrix that is derived from the pre-flare magnetic field. Ribbon 1, however, only roughly matches the separatrix. The probable main reason for the slight discrepancy of ribbon 1 is that the field of view of the *HSOS* vector magnetogram is too small and ribbon 1 is very close to the edge of the field of view. With full-disk vector magnetograms, such a problem is expected to be solved.

Flare kernels and ribbons were often found to be almost cospatial with the intersection of separatrices or QSLs with the solar surface [18, 19, 20, 21, 22, 23, 24]. They related the ribbons to the reconnection area, which tends to be a magnetic null point or QSL. In their works, they generally picked up the flare ribbon images during the flare process. According to the reconnection model, flare ribbons should be located at the footpoints of the inner separatrix (or QSL). However, we stress that the inner separatrix (or QSL), which is directly linked to the reconnection area, might be difficult to derive with the current techniques of magnetic field extrapolation. The derived separatrix in this paper, and in some of the previous works, actually corresponds to the outer separatrix, whose footpoints are cospatial with the final location of flare ribbons. If we compare the flare ribbon at any time with the derived separatrix, the two might always be roughly cospatial, since in most flares the moving distance of a flare ribbon is only $\sim 10''$ (e.g., [25]), which is of the order of the spatial resolution of many previous telescopes. With the unprecedented resolutions of both vector magnetograms and UV images by *Solar Dynamics Observatory* (*SDO*), more accurate comparisons between magnetic separatrix and the final location of flare ribbons will be very meaningful.

The prediction of the flare occurrence is improving gradually. In this paper we tentatively propose a theoretical conjecture to predict the final locations of flare ribbons before the flare occurs. By assuming a suitable reconnection rate, we can even further predict the lifetime of a flare before it occurs, which will greatly enhance our capacity of space weather forecast.

The research is supported by the Chinese foundations NSFC (11025314, 10878002, and 10933003) and 2011CB811402. PFC is also supported by an open research program of National Astronomical Observatories of China.

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