Magnetic Separatrix and Coronal Loop Heating in an Active Region

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Abstract

Although coronal heating is basically due to magnetic fields, it has been unknown why some field lines show up as coronal loops and the others do not. Based on the study of magnetic fields and coronal loops in active region NOAA 7321, we propose that only a subset of field lines constituting the magnetic separatrices are illuminated. Some coronal loops are much brighter than the others, indicating that there is enhanced heating in a limited subset of coronal loops. Such enhanced heating is ascribed to the magnetic shear at the loop foot-points or to the emerging magnetic flux.

Key words: Sun: magnetic fields — Sun: activity — Sun: corona

1. Introduction

Coronal loops are believed to align along magnetic field lines. A dense and hot plasma contained in a magnetic flux tube does not diffuse across the field lines because of high electrical conductivity of the hot coronal plasma (the so-called 'frozen-in' situation). The heat does not diffuse across the field lines either, because of vanishingly small cross-field heat conduction in a magnetized plasma. Therefore, once a concentrated heat input is given to a coronal flux tube, it will show up as a coronal loop and stays so until the heating ceases and the contained plasma cools to the ambient temperature.

Generally the corona is brighter where the field strength B is larger. One could expect that the heating rate is some increasing function of B. However, not all the coronal field lines become bright as coronal loops. Therefore, the magnitude of heating is not only a function of magnetic field strength. The spatial variation of the field strength is much smoother than the spatial variation of the brightness of coronal loops, as shown schematically in figure 1.

Then what is the additional factor that determines whether a particular field line is illuminated or not?

1. One could argue that the heating originates from a driving motion V on the solar surface, so that the loops may form where V is large. However, photospheric convective motions are nearly uniform in space, or even slightly suppressed in strong-field regions. It is unlikely that a modulation in V can lead to discrete loop structure.
2. The driving motion V has a frequency spectrum. If the heating is due to some resonance process, what is important is not only the magnitude of V, but also its power spectrum $V(\omega)$. If the resonant frequency or the power spectrum is highly non-uniform, that non-uniformity will translate itself into the brightness distribution of coronal loops. The power spectrum peaks around the five-minute period, but the peak is broad. The resonant frequency depends on the Alfvén speed and the length of field lines, and may not be a very non-uniform function. Furthermore, a typical resonance period of loops (tens of seconds) does not match the five-minute power peak.
3. It may be that dB/dt, not B itself, is an important factor. It is well known that the emergence of new magnetic flux leads to various activities. Some of the loops could be energized by flux emergence.
4. Not B itself, but curl $\boldsymbol{B}$ could be an important factor. Falconer et al. (1997) found that the brightest coronal loops are characterized by sheared magnetic fields at the foot-points.

In this paper, we will pay attention to the separatrix in the magnetic field configuration. The separatrix is the surface which divides the magnetic flux into separate systems. Two adjacent starting-points located on both sides of the separatrix surface will be connected by field lines to two end-points that are widely separated. The motions at the end-points which are arbitrarily different are mapped to two nearby starting-points, yielding discontinuity across the separatrix. The concept of separatrix has been introduced (Gorbachev and Somov 1988) and further developed (Démoulin et al. 1997; Longcope and Silva 1998) in the frame work of flare processes, but here we apply it to the loop heating problem.

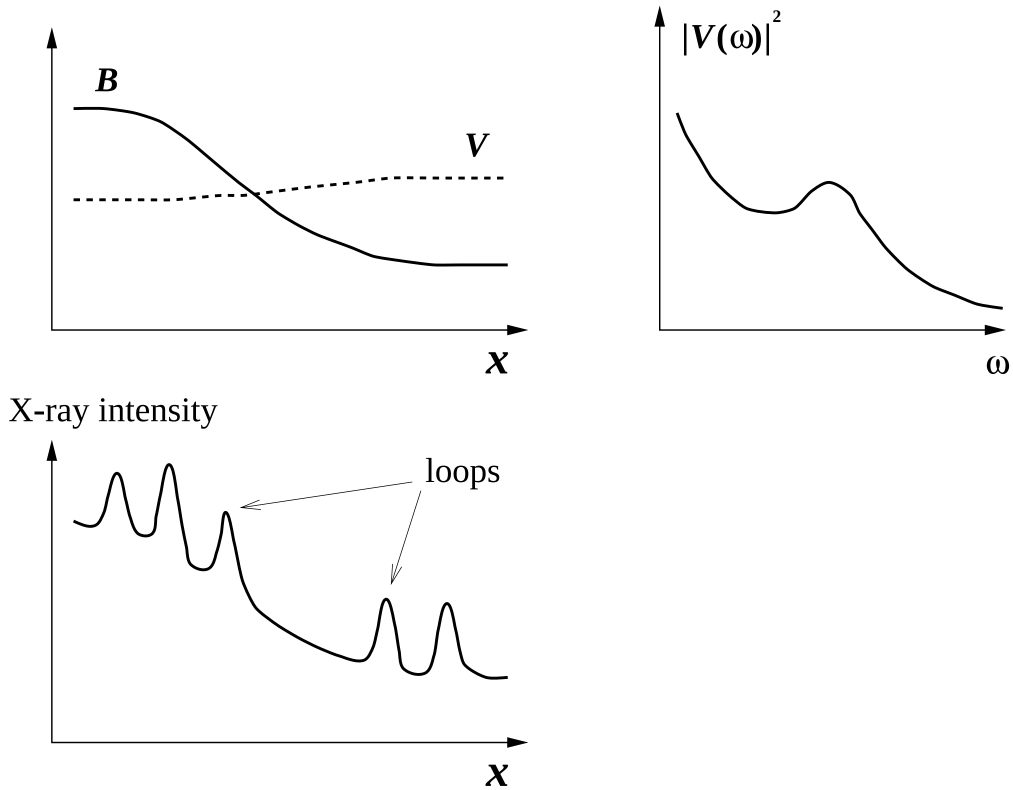

Fig. 1.. Schematic profiles of magnetic field strength B and velocity field V (top-left), and coronal X-ray brightness (bottom-left). The right-hand panel shows a schematic power spectrum of V.

2. Identification of Separatrix

Démoulin et al. (1997) introduced a slightly modified definition for the separatrix. We designate the starting-point of a field line on the $z = 0$ plane as $(x_\mathrm{s}, y_\mathrm{s})$ and its end-point as $(x_\mathrm{e}, y_\mathrm{e})$. After we integrate many field lines, we may evaluate the distribution of the foot-point separation factor N by

$$N = \left(\frac{\partial x_\mathrm{e}}{\partial x_\mathrm{s}}^2 + \frac{\partial y_\mathrm{e}}{\partial y_\mathrm{s}}^2 \right)^{1/2} . \tag{1}$$

A large value of N indicates that the mapping of field lines is nearly discontinuous. A real separatrix arises if $N = \infty$, but a sufficiently large value of N is physically meaningful. For example, $N = 100$ means that the foot-point separation is magnified by 100 times if one follows two nearby field lines. Démoulin et al. (1997) called the locus of large values of N as 'a quasi-separatrix layer'. We will use this approach to identify (quasi-)separatrix layers.

3. Separatrix and Coronal Loop Heating

As an example, we picked the data set on 1992 October 26 for the active region NOAA 7321. Coronal images were taken with the soft X-ray telescope (SXT) on board Yohkoh (Tsuneta et al. 1991). On this day, the region was quiet and showed no flare activity. Vector magnetograms and Hα images were taken with the Solar Flare Telescope at Mitaka (Sakurai et al. 1993). About 150 frames of magnetograms in 3-minute cadence were obtained. Hα images were taken every 10 seconds.

In order to compute magnetic field lines, we have to introduce a model for coronal magnetic fields. Here we assume that the coronal magnetic field is force-free, and apply the method developed by Yan and Sakurai (1997) to numerically compute the field lines, using vector magnetograms as the boundary condition.

Figure 2(a) shows the magnetogram of NOAA 7321 on October 26. From this data, we computed many force-free field lines and obtained the distribution of N, the foot-point separation factor. Figure 3(a) shows the distribution

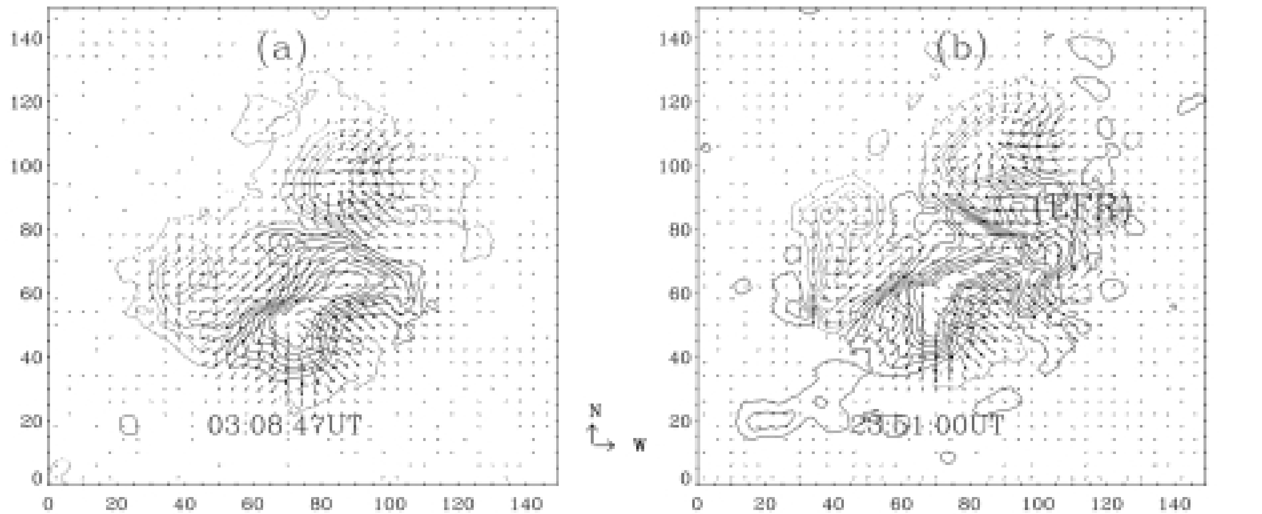

Fig. 2.. Vector magnetograms of NOAA 7321 taken at Mitaka on 1992 October 26, (a) at 0308 UT, (b) at 2351 UT. Panel (b) was taken on the next day in local time. Positive and negative longitudinal fields are represented by solid and dotted contours. Arrows indicate transverse magnetic fields. The plotted field is $200 \times 200''$.

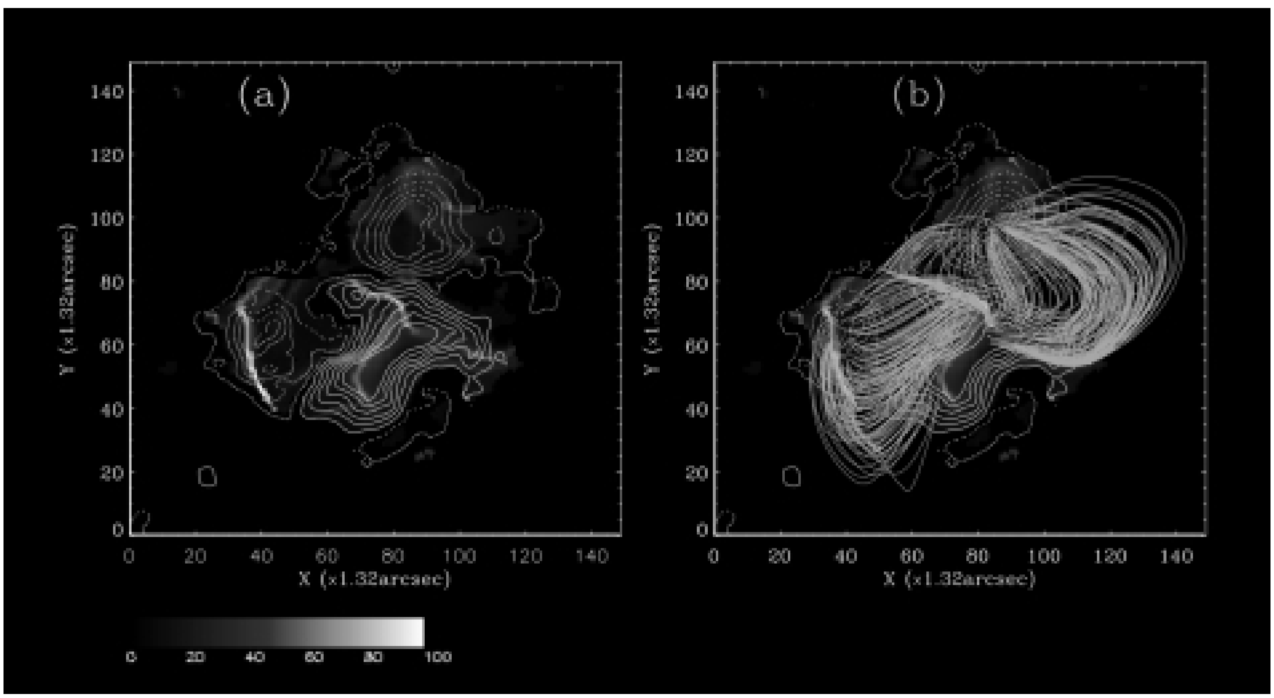

Fig. 3.. (a) Gray-scale map of N superposed on the contours of longitudinal magnetic fields. The scale for N is shown at the bottom. (b) Field lines rooted in the region of $N > 10$. These field lines constitute the three-dimensional separatrix surfaces.

of N in gray scale, overlaid on contours of longitudinal magnetic fields. The maximum value of N was found to be about 100. Large values of N are concentrated in narrow bands, which are the photospheric cross-section of the (quasi-)separatrices. In figure 3(b) are shown field lines coming from regions with $N > 10$. These field lines define the three-dimensional structure of the separatrices.

In figure 4 we compare the separatrices and the X-ray image. We can immediately see that only the field lines constituting the separatrices show up in X-ray coronal loops. Some field lines are brighter than the others, but where there are no separatrices, no active-region coronal loops are found.

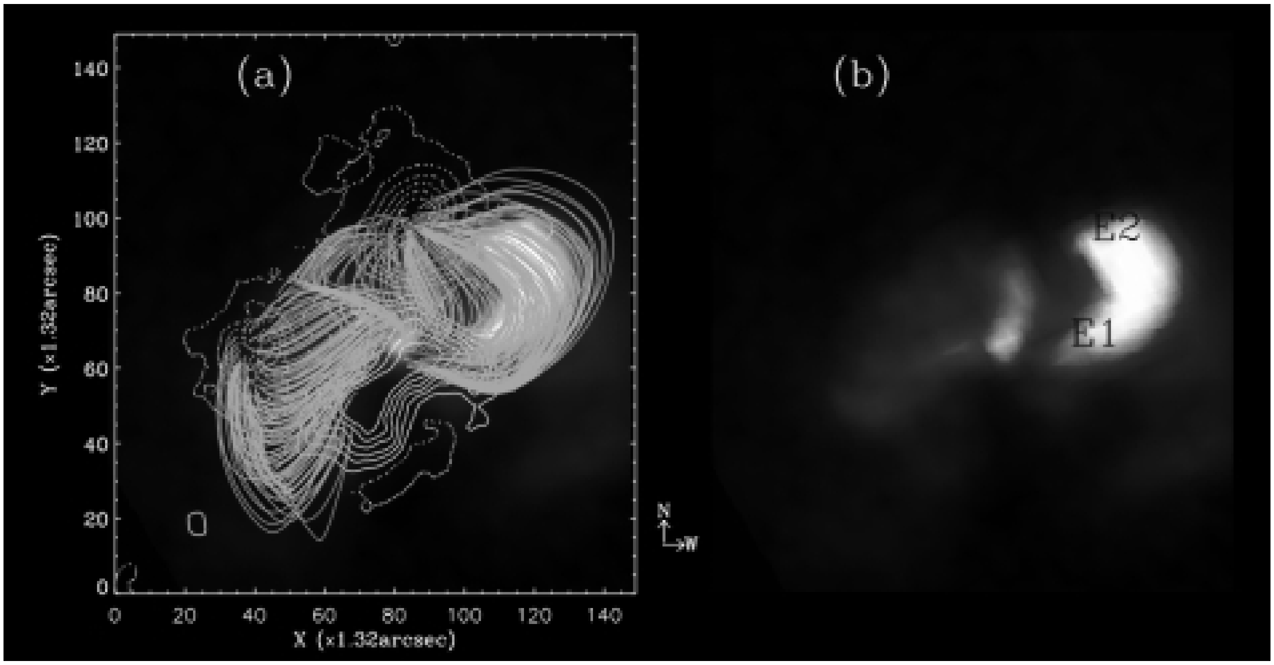

Fig. 4.. Comparison between the separatrices (a) and coronal loops (b). Contours in (a) indicate longitudinal magnetic fields given in figure 2(a). Symbols E1 and E2 in (b) designate the foot-point areas of a bright loop.

Figure 5 compares the separatrices and the chromospheric Hα structure. Here we define the chromospheric cross-section of the separatrices by looking at the portion of the separatrix field lines below $4''$ (2800 km). The bright plage areas nicely correspond to the chromospheric cross-section of the separatrices.

In figure 4(b) we can identify a particularly bright loop connecting the foot-points E1 and E2. In figure 5(b) we also find brighter Hα plage patches at E1 and E2. In the magnetogram of the next day (figure 2(b)), we see that an emerging flux region was situated below the loop connecting E1 and E2. Therefore, the enhanced heating of the loop connecting E1 and E2 could be due to the emergence of new magnetic flux. It can also be noticed that the magnetic neutral line running east-west between the two major sunspots evolved and increased its complexity, and the magnetic shear there increased as well. As Falconer et al. (1997) have already pointed out, magnetic shear can be a factor for enhanced coronal loop heating.

4. Conclusion

We have shown that magnetic separatrices correspond to coronal loops and bright Hα plages. The brightness of coronal structures is modulated within the separatrix layers, and coronal loops are particularly enhanced where flux emergence or strong magnetic shear are present. It is needless to say that the observational test of the hypothesis on the separatrix and coronal loop heating has to be worked out on much more data sets, and the present report is an initial attempt. Extremely fine-scale structures revealed by the TRACE mission indicates that some other (more basic) mechanism is at work to create fine structures within the separatrices. Ofman et al. (1998) suggest that an intermittent heating and chromospheric evaporation may make such a small-scale inhomogeneity in heating.

The separatrix is a layer of discontinuous linkage of field lines, and the discontinuity in the corona will be created depending on how discrepant the motions are at the distant ends of the separatrix field lines. If the horizontal surface flows can be inferred from correlation tracking technique, for example, we will be able to estimate the degree of discontinuity (or magnitude of sheet currents) in the separatrices. The X-ray brightness of coronal loops may also depend on the strength of the sheet currents. This is an important point to be studied in the future.

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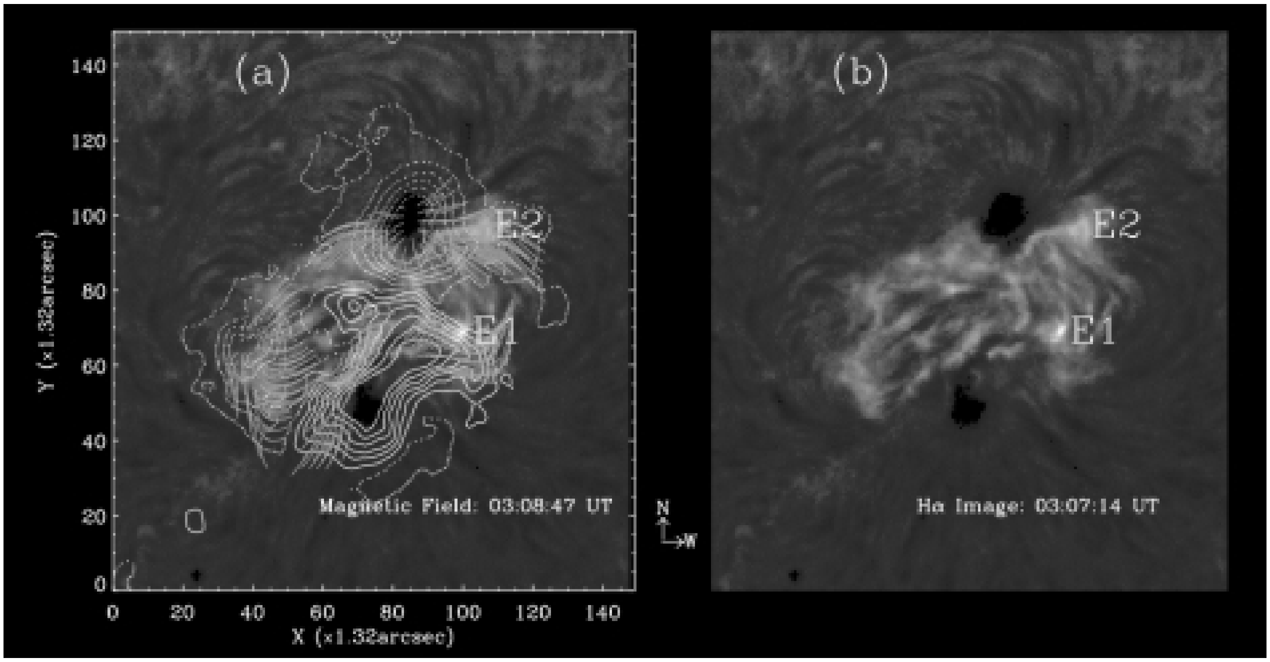

Fig. 5.. Comparison between the chromospheric cross section of the separatrices (a) and the Hα image (b). In (a) only a portion of field lines $z < 4''$ is drawn, overlaid on the contours of longitudinal fields. Symbols E1 and E2 correspond to the same symbols in figure 4(b).

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