Chapter 5
Magnetic Topology of Active Regions [1]

5.1 Introduction

5.1.1 Magnetic Reconnection in Solar Flares

A theoretical understanding of solar flares requires knowledge of the magnetic topology of flaring active regions and its relation to the places where magnetic energy is presumably stored and released for later conversion to particle energy and mass motions. The simplest model is a 2D quadrupolar field with an X-type null line (or X-point). If the plasma in the corona is treated as an ideal fluid, a current sheet will develop near the null line (Syrovatsky 1971, 1981; Biskamp 1986; Podgorny & Syrovatsky 1981; Podgorny & Podgorny 1992). Current sheets are also expected to form along the separatrix surfaces attached to the X-line (Low & Wolfson 1988; Lau & Finn 1990; Vekstein, Priest & Amari 1991; Finn & Lau 1991; Vekstein & Priest 1992). Various aspects of current sheet formation and magnetic reconnection for 2D models have been studied by other authors (Parker 1963; Petschek 1964; Sonnerup 1970; Yeh & Axford 1970; Sonnerupt & Priest 1975; Vasyliunas 1975; Forbes & Priest 1987; Priest, Parnell & Martin 1994).

On the other hand, it has long been recognized that an X-type null line is structurally unstable; a small perturbation will destroy the null line, resulting in isolated nulls (also called neutral or singular points). At the opposite of null lines, the null points are usually structurally stable. This leads to the study of 3D models with two bipolar flux regions in the photosphere (Sweet 1958, 1959; Baum & Bratenahl 1980; Hénoux & Somov 1987). In these configurations, regions of different connectivity are separated by magnetic surfaces called separatrics. The intersection of these separatrics is the separator which connects two nulls (so called also a null-null line). Along it, the field strength is in general finite but not constant. A finite field component along the separator does not stop the reconnection process, but it has been argued that it can significantly slow down its rate (Somov & Titov 1985). Since in these regions the resistivity is locally enhanced, separatrices and in particular, the separator are natural places for reconnection, where magnetic linkages can change and the stored magnetic energy can be released efficiently (Priest & Forbes 1992). Using a kinematic reconnection approach where the field is 3D and time dependent, Lau & Finn (1990) found different characteristics for the process occurring in 3D models with and without nulls. With nulls, singularities in the velocity field are stronger at the separator and at the nulls. In the absence of nulls, the singularities in the velocity are present on the separatrices (when they exist) with the same dependence as in $2\frac{1}{2}$D (**B** has three components in 2D) models. Recently Priest & Démoulin (1995) proposed that magnetic reconnection may also occur at the 'quasi-separatrix layers' (QSLs) in the latter case, which are the generalization of the separatrices, where the field-line linkage

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changes drastically but not generally discontinuous. The 3D characteristics of magnetic reconnection are highly complex and are only just beginning to be understood (Hesse & Schindler 1988; Schindler et al. 1988; Kusano et al. 1994; Priest & Titov 1995; Bungey et al. 1995).

The evidence of magnetic reconnection as the flare trigger mechanism can be offered by the link between observed chromospheric flares and the magnetic topology of active regions. Because if reconnection takes place in the separator and separatrics (or QSLs) of the corona, the energy released may not be confined to a localized area but can be transported through magnetic links to different places in the chromosphere. Gorbachev & Somov (1988, 1989) were the first to investigate such relations quantitatively. Since then, an increasing number of investigations have been clearly related the location of chromospheric flares to topological features of the magnetic field of active regions (Mandrini et al. 1991, 1993, 1995, 1997; Démoulin et al. 1993, 1994a; Hénoux et al. 1993; Van Driel et al. 1994; Bagalá et al. 1995). In all the studies, Hα kernels were found at the intersection of the separatrices (or QSLs) with the chromosphere, the kernels being magnetically connected to each other and to a common region around the separator. The results support reconnection driving energy release in solar flares. On the other hand, the presence of electric currents, flowing near the separatrices and crossing the chromosphere at the location of the chromospheric flare kernels, seems to indicate that the released energy is presumably stored in these field-aligned currents (see, e.g. Hénoux & Somov 1987, and references above).

5.1.2 Determination of the Topology of Magnetic Configurations

In 2D configurations the magnetic topology is defined by the presence of discontinuities in field-line linkage. The complexity of the mapping of field lines is reduced to the properties of a flux function. A constant value of the flux function at null points or at field lines tangent to the boundary defines the limit between different connectivity volumes or cells. In 3D configurations the design of a method, both closer to reconnection theory and to the observations, is not easy. This is not only because several properties of 2D or $2\frac{1}{2}$D configurations cannot be generalized to 3D, but also because a physically appropriate extrapolation for the coronal magnetic field needs to be considered deliberately. In the following, we review several methods finding the magnetic topology and present their limitations.

In 3D discontinuities occur only when nulls emerge (initially on and then above the photosphere). Thus the nulls and associated topological structures are physically important in understanding the characteristics of 3D configurations. The properties of nulls have been well studied by some authors (Fukao et al. 1975; Greene 1988; Lau & Finn 1990; Lau 1993). In the vicinity of a null, located at $\mathbf{x}_0$ say, the magnetic field $\mathbf{B}(\mathbf{x})$ is given (to first order) by

$$\mathbf{B}(\mathbf{x}) = \nabla\mathbf{B} \cdot (\mathbf{x} - \mathbf{x}_0) \tag{5.1}$$

where $\nabla\mathbf{B}$ is the 3×3 matrix. The structures of the field near $\mathbf{x}_0$ is determined by three eigenvalues and the corresponding eigen vectors of $\nabla\mathbf{B}$. For a magnetic field in equilibrium with a gas ($\mathbf{j}\times\mathbf{B}=\nabla$P) and in particular in the force-free limit, Lau & Finn (1990) showed that the eigenvalues are real. Then nulls are divided into two different types, called A and B, according to their eigenvalues. The type A null has only one positive eigenvalue, associated to the eigen direction γ_A. The other two negative eigenvalues are associated

with directions that are orthogonal to γ_A and define locally a plane, called Σ_A. Field lines along Σ_A approach the null from any direction, then they leave it by following the line γ_A (called an eigen field line). For nulls of type B the field is just reversed (two positive and one negative eigenvalues). The above local definition of Σ_A, which applies also to Σ_B, determines not only the field structure near the null of type A and B, but also the whole topology of the field: Σ_A and Σ_B extend to form the separatrices of the configuration. When one null of each type is present (A and B) the intersection of Σ_A and Σ_B surfaces defines the separator. The eigen field lines can be found easily by tracing field lines forward (backward) from an A(B) null. Locating the separatrix surfaces Σ_A and Σ_B is more difficult because of divergent effects on the surfaces. These effects are most prominent when the surfaces approach a null.

A convenient way to find the location of the separatrices is to take into account the magnetic linkage between a series of subphotospheric sources in terms of poles or dipoles, since the observed flux concentrations of the photospheric magnetic field can be approximately modelled by these sources (Démoulin et al. 1992), the method being called SM (for Source Method). Baum & Bratenahl (1980) were the first to calculate numerically the topology of a potential configuration formed by four magnetic poles. The next step, to represent in a better way the observed magnetic field, was to introduced many sources (Mandrini et al. 1991, 1993) and to determine their positions and intensities fitted by least squares to the observed magnetic data (Démoulin et al. 1994a). In these cases many separatrices can be present and the sources should be gathered in groups; that is to say, all sources used to describe the observed complex shape of a magnetic field concentration belong to the same group. The connectivity of a field line is defined by the groups to which the sources, found at both of its ends, belong. The SM has two main limitations: first, one needs to integrate below the photosphere along a few thousands kilometers, where a magnetic field model is not available; second, it cannot be used with other extrapolation techniques because it intrinsically needs sources to define the connectivity.

Another way to locate the separatrices is to look for discontinuities in functions such as the field line length (L) or the distance (D) between field line footpoints. The connectivity of field lines changes across a separatrix surface, thus L or D suffers a jump at points lying on the separatrix surface. Lau (1993) showed that it is better to use the delay function, defined as

$$T_{\pm}(\mathbf{x}_0) = \left| \int \frac{ds}{B} \right| \tag{5.2}$$

where s is the arc length of a field line and $B{=}|\mathbf{B}(\mathbf{x})|$. The integration starts from $\mathbf{x}_0$, goes forward (backward) along $\mathbf{B}$ for $T_+(T_-)$, and ends when the field line hits the boundary that is chosen to enclose the region of physical interest. When one encounters a field line that is related to a null or a quasi-null line, the delay function has a logarithmic singularity; that is to say, it is valid only for magnetic configurations having a separator above the photosphere. However, it has been found in several ARs that the presence of nulls is not necessary for the flares occurring (Démoulin et al. 1994). Recently, together with the new development that 3D magnetic reconnection may also occur in the absence of nulls at QSLs (Priest & Démoulin 1995), an algorithm called QSLM has been designed (Démoulin et al. 1996). In this method, QSLs are defined in terms of a dimensionless function called N. If one integrates, over a distance s in both directions, a field line passing at a point $\mathbf{P}(x,y,z)$ of the corona, the end points of coordinates (x',y',z') and (x'',y'',z''), define a vector $\mathbf{D}(x,y,z) = \{X_1,X_2,X_3\}{=}\{x''-x', y''-y', z''-z'\}$. A drastic change in field-line

linkage means that for a slight shift of point $\mathbf{P}(x, y, z)$, $\mathbf{D}(x, y, z)$ varies greatly. In the solar case, the distance s to be used is the distance to the photosphere ($z' = z'' = 0$) and the expression for $N(x, y)$ is

$$N(x, y) = \sqrt{\sum_{i=1,2} \left[\left(\frac{\partial X_i}{\partial x} \right)^2 + \left(\frac{\partial X_i}{\partial y} \right)^2 \right]}. \tag{5.3}$$

Compared to the previous methods, QSLM is more general, which takes into account only the field-line linkage above the photosphere and without any reference to null points, on the other hand, which can be applied to any kind of magnetic field representation.

The aim of this chapter is to give a realistic diagnosis to the topological properties of the observed field in the photosphere, with a 2D method. Section 5.2 explains why the 2D method is significant in the study of magnetic topology and can be used to trace some peculiar structures in association with the separator or separatrics. Section 5.3 describes briefly the magnetic observations for AR7321 and lowpass filtering technique. In Section 5.4 we apply the 2D method to AR7321, and firstly obtain the observed field topology in 2D and compare it with that of a linear force-free field, extrapolated from the longitudinal field boundary. We further attempt to interpret its 2D topological properties in terms of 3D field-line connectivity patterns, and compare them with the flare and some less energetic events observed in H_β or SXR emission.

5.2 Saddle Points and Separators

With the introduction of source method (SM)(Démoulin et al. 1992), a number of studies are carried out in order to investigate the magnetic topology which may favor the energy release, or the flare, in an active region. A specially interesting configuration in the highlight has been the magnetic field consisting of one major bipole and a parasitic bipole (Gorbachev & Somov 1989; Mandrini et al. 1991, 1993; Démoulin et al. 1993, 1994a; Van Driel et al. 1994). Although the basic topology of such magnetic field can be well modelled by the approximation of four magnetic sources, there is difficulty in this method in modelling the complex configuration in an active region in reality. In one case, when the active region, such a field of super spot groups (e.g. AR5395, AR6659, and AR6891) is made up of many polarities with very fine structures, amounts of magnetic sources would be necessary and it is often hard to group these sources due to the complicated evolution of each polarity (Schmieder et al. 1994). In another case, the observed active region is characteristic of strong and localized shear, which requires a nonlinear force-free field model instead of the SM, while so far not yet a practical model can be applied (Mandrini et al. 1995). We hence tend to explore a different way not to presume a model as the representation of the field. In fact, since the structure of the field near the separatrices or separator is rather peculiar, some observational characters such as the arrangement of the chromospheric fibril or the photospheric transverse field can actually serve to approach our problem of interest concerning the magnetic topology and their relation with the flare energy release, at least in some cases (Filippov 1995; Wang & Wang 1996; Wang 1997).

For instance, when in a plane normal to the separator or separatrics, the 2D field pattern clearly reveals this structural peculiarity. For a separator, in the cross section, the intersecting point should be a singular point of X-type (or saddle point) where the horizontal field is zero. For a separatrix, the integral lines of the 2D field vectors are discontinuous in linkage on its intersection with a normal cross section; the field lines

demarcating the 2D magnetic cells of different field-line connectivities make the magnetic lanes, which pass through the singular points forming a network.

In general, for a 2D field, if magnetic poles are assumed to be singular points of node type, the geometrical properties near singular points can be mathematically described with Poincaré index with 1 or -1, and -1 is for the case of a saddle point (Arnold 1973; Bogoliubov & mitropolsky 1961). The Poincaré index of an isolated singular point is defined as the number of rotations of the 2D field vector along a closed curve surrounding the point with a finite diameter, i.e.

$$I = \frac{1}{2\pi} \oint_L d\theta, \tag{5.4}$$

where $\theta = tan^{-1}(B_y/B_x)$. A variety of 2D field patterns denoted by this index have been discussed in detail by Wang & Wang (1996).

In observations, one example of the topological properties of the 2D field is demonstrated by Filippov (1995) by virtue of the H_α filtergrams, in which the stable saddle points and the imprint of separatrices, looking like a fir-tree branch, were clearly outlined by the large-scale fibrils. In another example, using the Poincaré index, Wang & Wang (1996) determined the saddle points and magnetic lanes of the 2D field extrapolated by a potential model in the chromospheric plane, and found that these 2D properties were closely related to the location of $H\beta$ flare kernels The results not only confirm the feasibility of the idea to describe the field independent of a model, but encourage us further to diagnose the topological properties directly from the observed photospheric transverse field, which bears a nonpotential character favoring the flare occurrence.

However, it should be pointed out that the topology of a 3D field configuration as a global property, in general, cannot be entirely characterized by a local or a 2D criterion (Démoulin et al. 1996; Amari 1997). That is to say, if a special structure around certain point in the form of the 2D field is seen, it may originate only due to the perspective effect of a 3D field depending on the view angle, i.e. of the orientation of the cross section plane, but do not necessarily indicate the 3D singularity at this point (say, a separator passing through it). Such cases are shown by Priest & Forbes (1989) and Filippov (1995). Thus, we should be much careful in the study when the 2D topological properties are referred to as the 3D ones. Next, we would explain the physical validity of the 2D field properties, which are confined in the photospheric or chromospheric surface, in the study of magnetic topology and energy release in the flare.

Firstly, we can assure that the saddle point of 2D field gives the true position of a separator intersecting with a horizontal plane when the vertical field component in the saddle point is absent; in another words, the saddle point corresponds to a 3D null (Sweet 1958, 1969; Baum & Bratenahl 1980; Hénoux & Somov 1987). In this case, the origin of a saddle point associated with the separator do not need to be strictly in a plane normal to it, but can be in any planes passing through or near the null parallel to its eigen field lines (Lau & Finn 1990). These properties can be applied to set up a set of procedures to confirm the relation of the saddle points with the location of the separators (Wang 1997).

Secondly, from the model of magnetic sources, we can deduce that the saddle points are close to the possible intersections of the separators with the photospheric (or chromospheric) surface. It is known that the observations are in agreement with a convergence of the field flux to subphotospheric layers; consequently, the observed field concentrations can be modelled by the magnetic sources, which are situated below the photosphere generally with the depths of the order much smaller compared to the size of the active region. Using

4 magnetic charges, Démoulin et al. (1994b) modelled 10 datasets for 5 active regions, giving the average depth of 0.13 ± 0.06 for the main bipole and 0.06 ± 0.02 for the parasitic bipole if the size of the main bipole is normalized to unity, and found that the nulls were also present below the photosphere (with the depths less than 0.1) for most cases (nearly 90%), given that the intensity and relative positions of the charges, and the magnetic shear are known. In other words, all the magnetic charges and the major nulls are supposed to be situated in a thin horizontal layer. With this assumption, the separatrices and separators are nearly vertical near this thin layer (Baum & Bratenahl 1980; Govbachev & Somov 1988; Filipov 1995), thus we believe that the 2D magnetic lanes or the saddle points are not far from the 'true' location of the separatrices or separators in the photospheric (or chromospheric) surface.

Thirdly, since the separators or the separatrices are preferable places for energy release and at the same time are sites of structural stability, we may expect them to be morphologically associated with the observed manifestations such as homogeneous flares or repeated occurrences of energy releases. This also provides us an important referable evidence for confirming the 2D topology to the separator or separatrices.

For all above, however, a comprehensive comparison with models has to be made in the future work to identify more accurately the 3D properties in the 2D signature.

5.3 Observations

5.3.1 Active Region NOAA 7321

The active region NOAA7321 was a new emerging flux region (EFR), passing across the solar disk from October 24 to November 1 in 1992. During this period, it evolved from an explicit main bipole, nearly resembling the potential field, into a complicated configuration with strong shear around the magnetic neutral line when several new satellite spots continuously emerged from between the two main poles (Zhang 1995). On October 27, the active region was located at the position (S23, W18) with the most fully developed morphology, and a series of flares occurred in the emerging region, related to the observed strong shear. Thus, we take the observed fields on that day to investigate the 2D topological properties.

The photospheric magnetic field of AR7321 was observed by a vector magnetograph system (Ai & Hu 1986), installed at the Huairou Solar Observing Station (HSOS) of Beijing Astronomical Observatory. To reduce the noise, and to match the practical spatial resolution, a $2'' \times 2''$ smooth average on the Stokes parameters V, Q and U is made, then the obtained magnetograms with 157×109 pixels. After the 180° ambiguity is resolved for the transverse field components by a multistep method (Wang et al. 1994), the vector magnetograms are transformed into the heliospheric plane. In addition, we also obtained Hβ filtergrams for a 1N/M1.1 flare on Oct. 27 from HSOS and observations of the SXR emission during 00:48UT–07:58UT from *Yohkoh* SXT (Tsuneta et al. 1991).

Figure 5.1 shows two vector magnetograms, for which the projection effect has been removed. It is seen that a magnetic neutral line (thick solid style) divides the whole active region into two parts: the negative polarity region, containing three main poles (S1, S2 and S3) loosely each other, and the positive region containing two compact poles (N1 and N2). S1 and N1 appeared on Oct.24, making a main bipole; S2 and N2 emerged on Oct.25 and developed strong on Oct.26; S3 appeared on Oct.27. The formation of observed shear and its relation to flux emergence were studied in detail by Zhang (1995).

5.3.2 Fourier Filtering Method

In order to detect the singular points and trace the integral lines of the transverse field components to recover the 2D field pattern of connectivity, we employ a lowpass filter technique to further improve the quality of the observed raw magnetograms. The pretreatment is proved efficient in reduing measurement noises, but influencing a little on the main structures, which meet our study preferable to the large-scale properties. In the following we describe the Fourier filter method and the reductions of our data.

In the Cartesian coordinate system, we use $B_{s0}(x,y)$ and $\hat{B}_{s0}(u,v)(s = x,y,z)$ to represent the observed field components and their Fourier components, respectively. Then the filtered components, $B^*_{s0}(x,y)$, are

$$B^*_{s0}(x,y) = \sum_u \sum_v F(u,v)\hat{B}_{s0}(u,v)e^{2\pi i(xu+yv)}, \tag{5.5}$$

In Eq.(5.5) $F(u,v)$ is a filter function, taken as the butterworth form, i.e.

$$F(u,v) = \frac{1}{1+k(u,v)/k_c},$$

where $k(u,v) = 2\pi(u^2+v^2)^{1/2}$, and k_c is the lowpass cutoff frequency. Resolution accuracy of the observed magnetograms decreases due to the filtering, we so evaluate the new one by

$$h^*_x = \frac{L_x}{2\bar{k_c}} \qquad and \qquad h^*_y = \frac{L_y}{2\bar{k_c}}. \tag{5.6}$$

In Eq.(5.6) $\bar{k_c}$ is the relative cutoff frequency, defined as

$$\bar{k_c} = \frac{k_c}{2\pi\sqrt{1/L_x^2+1/L_y^2}},$$

where L_x and L_y are typical sizes of an active region.

The major structural loss of the observed field suffered in the filtering is evaluated by defining a parameter, e_s,

$$e_s = \left[\frac{1}{N_xN_y}\sum_{x=1}^{N_x}\sum_{y=1}^{N_y}(B_{s0}(x,y) - B^*_{s0}(x,y))^2\right]^{\frac{1}{2}}, \quad (s = l \ or \ t), \tag{5.7}$$

where $B_{s0}(x,y)$ satisfies the condition, $|B_{s0}(x,y)| \geq 3max(|\delta_s|, \Delta\delta_s)$, to select main structures of the field. δ_s and $\Delta\delta_s$ (s=l or t) are the average value and the standard deviation of measurement noises for the longitudinal and transverse field components, estimated in a weak field area.

Table 5-1 Parameters defining the measurement noise level and the filtering loss of main structures for the longitudinal component (B_l) and the transverse component (B_t) of the observed field at 01:44UT on October 27. δ_s, $\Delta\delta_s$ and e_s ($s = l$ or t) are in units of gauss.

k_c	–	20	10	5
δ_l	-18.1	-17.8	-17.3	-17.2
$\Delta\delta_l$	121.2	78.8	56.9	36.2
e_l	–	98.3	160.2	235.4
δ_t	186.2	126.2	98.2	72.4
$\Delta\delta_t$	118.5	79.2	64.3	47.6
e_t	–	107.2	164.1	240.4

We apply the Fourier filter to the vector magnetogram observed at 01:44UT on Oct.27, for the cutoff frequencies $\bar{k_c}$ =20, 10 and 5, respectively corresponding to the effective resolutions of 4×3, 8×6 and 16×11 pixels by Expr.(5.6). The measurement noise levels and the filtering loss parameter are listed in Table 5-1, in which the first column for the case without filtering. Table 5-1 shows for the raw data that the noise level of B_t is nearly 10 times larger than that of B_l, but their deviations are similar; whereas for the filtered case of $\bar{k_c}$=5, the deviations of both B_t and B_l reduce by about 2/3, but the maximum filtering loss increases by less than the order of the raw measurement noise levels (estimated as $3\Delta\delta_s$). The evaluations indicate that the lowpass filter has only a trivial influence on the main magnetic structures for the cases of given values of $\bar{k_c}$, so the 2D magnetic topology of interest can be expected to remain yet, after filtering.

5.4 Singularity in the Observed Vector Field

5.4.1 2D Topology of the Observed Transverse Field

We take the vector magnetogram observed at 01:44UT to demonstrate the procedures of 2D method in determining the observed field topology in the photosphere. Firstly, we use the Poincaré index defined as Eq.(5.4) to derive the singular points from the transverse field component. Figure 5.2 presents the distributions of obtained singular points for the raw data case and for the filtered cases, $\bar{k_c}$=20, 10, and 5. The node points with the index of $I = 1$ are marked by the symbol, '◯'; the saddle points with $I = -1$ are marked by '◇'. We find that for the raw case (Fig.5.2a), there exist a large number of candidate points, but the majority are nearly scattered over the weak field regions, implying that their origin is greatly due to the measurement noise. It is also possible that some of them are created by small-scale fields, however, we here pay more attention to those associated with the large-scale field patterns. It is well discerned through comparisons that the filter can reject most of such 'sham' points not interesting to us. Secondly, we trace the integral lines of the transverse field directions to show the 2D field patterns of connectivity. In Fig.5.2, 46 integral lines of the field are drawn in each case. We see that the filter makes the 2D large-scale field-line linkage more clearly exhibited in the active region. Thirdly, we identify the singular points of interest in combination with the property of the large-scale field line patterns, and pick out the four field lines closer to each saddle, in which any couple of neighboring ones start from the same node at one end, but reach the different nodes at another end, and form a lane between them, connecting a node with a saddle. In Fig.5.2, our interested singular points are shown with the bold color, which are characterized by the special field-line patterns. In particular, the selected field lines around each saddle are described by the bold curves (in Fig.5.2c). Besides, we notice that in the case $\bar{k_c}$=5, although some singular points cannot be calculated by the Poincaré index (marked by the small boxes with dash line in Fig.5.2d), the special field-line patterns are still distinctive near these positions. This indicates that the filter would have only a little effect on disclosing the 2D large-scale topology of the observed field, as expected in Sect.5.3.2.

Following three steps above, we first obtain the 2D magnetic topology of an active region from the observed transverse field. Figure 5.3 shows two cases for AR7321, one at 01:44UT with the filter $\bar{k_c}$=10, the other at 04:12UT with $\bar{k_c}$=20. They have the similar field topological configurations, characterized by six nodes (C1, C2, ···, and C6) and three saddles (P1, P2, and P3). The magnetic lanes (bold curves) linking these singular points demarcate the 2D field lines of different connectivity into nine cells, which can be divided

into two classes, called L and H. In L-class cell (including L1, L2, L3 and L4), the 2D field lines connect two parts of a cell with opposite polarities, which can be supposed as low magnetic loops projected onto the photosphere. For instance, those in L1 and L3 connect the main poles with the emerging poles (C1 with C3, and C2 with C5); those in L2 and L4 connect the emerging poles (C3 with C4, and C3 with C6). In H-class cell (including H1, H2, H3, H4 and H5), the flux of a cell has the same polarity, where the 2D field lines converging at a node extend to the weak field in the distance. There may exist high magnetic loops connecting with these cells from flux evolution, such as between H1 and H2. We will confirm these suggestions on the 3D model in Sect.5.4.3. Moreover, Figure 5.3 shows another distinct character that the cells (L1, L2 and L3) around the magnetic neutral line (drawn in middle thick solid line) are of strong shear, in contrast with the main bipole cells (H1 and H2) nearly potential. Such topological complications, for the observed field, brought by flux emergence, will be investigated in the next section.

5.4.2 Topological Comparison with Linear Force-Free Fields in 2D

It is known that potential and linear force-free field models are still the principal way to study the spatial configuration of a magnetic field or the field topology above the photosphere, although α (defined as $\nabla \times \mathbf{B} = \alpha \mathbf{B}$), in all likelihood, is not a constant everywhere within an active region (Gary et al. 1987; Démoulin et al. 1994a; Amari et al. 1997); because nonlinear force-free fields are generally very difficult to construct (Mandrini et al. 1995; Démoulin et al. 1992). With such models, 3D fields can be computed from the longitudinal component of the observed field, and compared with the field line tracers such as chromospheric fibrils and coronal bright structures. In addition, the computed transverse field in the photosphere can also be directly compared with the observed transverse field to show where in the active region and to what degree the observed field is nonpotential. In this section, we concentrate on the 2D topological comparison between the computed and observed fields in the photosphere, to look into particular features of the observed fields caused by flux emergence or photospheric motion.

We use the Fourier Transform Method (FTM) (Nakagawa & Raadu 1972; Alissandrakis 1981) for force-free magnetic field computation. This method requires an isolated active region having net zero flux on the source surface. For the longitudinal magnetogram taken at 01:44UT, we estimate the positive/ negative flux as $4.35/-4.22\times10^{21}\mathrm{Gcm}^2$ above the noise level 120 G, so the condition of net flux balance can be well satisfied to within 3%. Moreover, since the active region (covering 85×85 pixels) is just centered in the magnetograms, the effect of aliasing in FFT extrapolation is also negligible (Alissandrakis 1981).

In Figure 5.4 we show the 2D topology of the computed transverse fields in the photosphere derived from the observed longitudinal field, on the assumption of a constant α for the potential case (α=0) and for three nonpotential cases, α=0.03, 0.06, and 0.09 in units of $0.69\mathrm{Mm}^{-1}$. Similarly to the observed field case, we have done a filtering on the computed field with $\bar{k}_c$=10. We find that the computed field is distinctly different in 2D topology from the observed field. The saddle P3 which separates the emerging pole C3 from the main pole C2 in the observed case (Fig.5.3a), is absent in the cases for the computed field; this leads to a merging of the associated cells L2 and L3 into one cell, L23. For α=0 and 0.03, the L-class cells L1, L23, and L4 appear to share a common pole, C2, in the positive polarity region (Fig.5.4a and b); the nodes C1, C4 and C6 are directly connected with the node C2, while in the observed field, they are magnetically

linked with the node C3, corresponding to an emerging pole. In addition, in the negative polarity region S2, the cells H3 and H4, which are differentiated by the observed field-line patterns, also merge into one cell H34 in the computed cases, and only one node C4 (or C5) can be seen; for these two nodes, the relevant magnetic structures were formed at the different time (ref. Zhang 1995).

These distinctions imply that for such an EFR the topological connectivities of the actual field are involved with the evolution of magnetic structures. For example, the new magnetic polarities (S2 and N2), emerged between the two main poles (S1 and N1) (Fig.5.1), formed a low field-line cell (L2) which separates the 2D field linkage of the main bipole in the photosphere. Since the emerging field loops were strongly sheared with the main ones in high-spanning, we cannot exclude the possibility that the cells L1 and L3 were born of the partial reconstruction between these two sets of field line systems by interaction (Hénoux & Somov 1987, Mandrini et al. 1993). We thus argue that such topological features of the observed field, favorable to flare occurrence, are difficult being interpreted by field extrapolation only depending on the distribution of the photospheric magnetic flux unless a possible nonlinear force-free model adding in the observed transverse field boundary is developed (Amari et al. 1997).

Next, we look at the effect of nonpotentiality on the 2D topology by modelling the observed shear. With the increase of α, we find that the field-line patterns of the cells L1 and L23 are approaching to the actual look. For α=0.06 and 0.09 (Fig.5.4c and d), the node C2 shifts to the position of C3, and the node C4 shifts to C5, near which appears a new saddle having no counterpart in the observed field. We notice that the shear readily deforms the magnetic lanes in the location and shape, but hardly effects on the saddles, e.g. P1 and P2, showing that they have the stable structures. Besides, for the greater α, some 2D field-line connectivities crossing the old lanes seen in Fig.5.4c between H2 and L4, or in Fig.5.4d between H2 and L1, are of low physical meaning in constructing a new cell, which may arise from the limitations of the linear force-free field modelling (Démoulin et al. 1992, 1994a); because in this case, the great α is already far from representing these nearly potential regions correctly.

Finally, referring to the 2D field-line arrangements of the modelling fields for the different values of α, we can estimate the magnitude of average electric current with the parameter α for each cell. We obtain that the cells H1 and H2 for the main bipole approximate to the potential field with α=0; the cells H3, H5 and L4 have the values in range of $0< \alpha <0.03$; the cells L1, L2, L3 and H4 with great localized shear, $\alpha >0.09$, correspond to the emerging flux. These topological features of the observed field conform to the intrinsic definition of magnetic cells, (i.e. containing the magnetic flux of different origin and subject to different photospheric evolution, so inducing different currents), therefore are significant in understanding magnetic energy release in this active region.

5.4.3 3D Field Line Patterns of the Modelling Field

We have analysed the 2D observed field topology in AR7321 from the transverse magnetograms, and find some special features which are favorable to occurring flares. For these 2D structures, we take much interest in their physical interpretation, i.e., their association with 3D topology (the separatrices or separator). But as have been discussed in Sect.5.2, the problem is not easy to solve. On the other hand, we still have no capabilities to acquire directly the complete magnetic field over the whole atmosphere to construct such an actual topology for comparison; although the field above the photosphere can also

be extrapolated using a force-free field model, a general solution is yet very difficult to construct. Thus, we abandon interpreting the 2D observed topology directly, instead, on a linear force-free field model, look into this problem preliminarily.

Separatrices are surfaces where the mapping of field lines is discontinuous. For the extrapolated field based on a continuous boundary, the search for such structures is difficult (Démoulin et al. 1992). Recently, Priest and Démoulin (1995) have proposed a way of generalizing the concept of separatrices to so-called 'quasi-separatrix layers' (QSLs), which are regions where there is a drastic change in field-line linkage, and magnetic reconnection may also occur. Furthermore, to find the location of QSLs above the photosphere, Démoulin et al. (1996) designed an automatic method called QSLM. By the definition, the field lines involved in QSLs, which initially close to one another separate widely over a short distance, are determined by a dimensionless function $N(x, y)$ representing the norm of the displacement gradient tensor, when mapping the field lines to the photosphere. The QSLM allows us to determine the field topology quantitatively, but requires the computation of thousands of field lines. We here, only aiming at our purpose, so locate the intersection of QSLs with the photosphere approximately by selecting some particular field lines.

Figure 5.5 shows the connectivity patterns of 3D field lines projected onto the photosphere, for the cases α=0 and α=0.06. The particular field lines are highlighted in thick solid style, which are clearly seen separating widely near the saddles. The dashed lines portray the starting points of these field lines, representing the location of the QSLs in the photosphere. We find that they are close to the portions of the 2D magnetic lanes determined by the transverse field, especially near the saddle points (Fig.5.5a). In the case of the field being strongly sheared (Fig.5.5b), the correlation features between the QSLs and the lanes are still present, but a divergence at region A appears more obvious, in fact, where the 2D field linkage is of low physical meaning due to the large α-value as discussed in Sect.5.4.2. In 3D configurations, we notice that the magnetic cells are not so easy to be determined as in 2D; the discontinuity of field-line linkage near the saddles is only topological feature we can refer to. Figure 6a-b show a side view of the particular field lines anchoring near the saddles for the two cases. The 'cavity' structure around the saddles infers the possible null beneath the photosphere. The whole space consisting of different field-line connectivities on large scale between a positive polarity region and three negative polarity regions is thus topologically divided into three regions (labelled with I, II and III) by these nulls and the separatrices (defined as the QSLs). However, in this way, it is impossible for us to locate the the cell boundary completely, because when the field lines reach at the grid edge, we are not able to decide their connectivities.

Table 5-2 Parameters of the magnetic loops above the photosphere, (a)for the potential case (α=0), and (b)for the linear force-free field case (α=0.06). HL represents the high loops; LL, the low loops. Z_{top} and L_h are respectively the height of the loop and its horizontal extension at the photospheric level (in arcsec). θ is the inclination of the loop to the photosphere.

(a)

Region I

HL	1	2	3	4	5	LL	6	7
Z_{top}	106	121	115	100	106		32	18
Z_{top}/L_h	1.3	1.4	1.4	1.2	1.3		0.57	0.39

Region II

HL	1	2	LL	3	4	5
hline Z_{top}	100	89		18	27	35
Z_{top}/L_h	1.4	1.3		0.41	0.53	0.59

Region III

HL	1	2	LL	3	4	5
Z_{top}	47	41		18	21	13
Z_{top}/L_h	0.81	0.67		0.42	0.45	0.22
θ	66°	56°		68°	49°	23°

(b)

Region I

HL	1	2	3	4	5	6	LL	7	8
Z_{top}	97	103	103	89	83	75		22	15
Z_{top}/L_h	1.1	1.2	1.1	0.95	0.82	0.87		0.36	0.27

Region II

HL	1	2	3	LL	4	5	6
Z_{top}	61	59	56		18	21	19
Z_{top}/L_h	0.69	0.73	0.66		0.36	0.37	0.30

For the portions of the lanes separating the L-class with the H-class 2D cells, we find no intersection of the QSLs correlated to them, which have no general meaning of separatrices. For example, in Region I composed of 2D cells H1, H2 and L1, in Region II of H34 and L23, and in Region III of H5 and L4, the 3D field-line linkage is continuous (Fig.5.5). However, it is worthwhile noticed that the top-viewed field lines whose footpoints are limited in the L-class cells are coincided with the alignments of the transverse field components (or the 2D field-line patterns) in the photosphere; they correspond to the low field-line linkage, while the field lines anchoring at the H-class cells correspond to the high linkage. Figure 5.6(c-d) demonstrate some field loops located at these regions. We find that two kinds of the loops are distinctly different in height and shape. For the potential case, the exhibited high loops in Regions I and II, have a height, Z_{top}, in the range 89″-140″ above the photosphere and an average ratio between their height and horizontal extension, Z_{top}/L_h, approximately 1.4 (Table 5-2a), while the low loops have the Z_{top} in the range 18″-56″ and the Z_{top}/L_h about 0.5. In Region III, we notice that the projection of field loops is well coincided with the 2D field-line pattern of the observed transverse field (Fig.5.5a), and these loops are inclined to the photosphere with an angle in the range 23°-68° (Table 5-2a). For the sheared field case (α=0.06), the average height of loops decrease compared to the potential case (Fig.5.6); the difference between two kinds of loops is distinctive yet; in Regions I and II, the high loops have the height in the range 75″-103″ and Z_{top}/L_h about 1.0; while the low loops have the height in the range 15″-22″ and Z_{top}/L_h about 0.33, and they are strongly sheared with the high loops, but their photospheric projection remains almost aligning along the transverse field. As a matter of fact, it is just these features for the low loop that can help us to infer the field topology in the low atmosphere, from the photospheric patterns of 2D field-line linkage.

5.4.4 Flare and High Energy Emissions

We know that a flare occurring in an active region can give out high energy emission in multi-wavelengths in the atmosphere from the low chromosphere up to the corona. The

soft X-ray emission originates from hot and dense plasmas confined by magnetic fields; its image can reveal the features of flaring loops showing the coronal field topology, while Hα (or Hβ) image can give us accurate information about the chromospheric field configuration and flare footpoints. In this connection, we take a correlation between the Hβ and SXR images and the 2D observed field topology. The purpose, on the one hand, is to examine the obtained actual 2D field topology indirectly, on the other hand, is to investigate the role of field topology in magnetic release of energy.

On October 27, 1992, many brightening events, including two 1N/M1 flares respectively at 00:20UT and 01:44UT, were observed in AR7321 (Suematsu & Tanaka 1993). According to their locations and morphologies in Hα, these two flares were identified homologous (Kawakami 1993). For the second flare, a complete set of optical, Hα (or Hβ), X-ray (SXR or HXR) and radio data exist, which have been analyzed to interpret the energy release and the coronal heating mechanisms (Takakura et al. 1994; Qiu et al. 1997; Wang et al. 1997). Figure 5.7a presents the coaligned observations of the flare in SXR and Hβ, overlaid with the 2D topology of the observed transverse field at 01:44UT. The X-ray emission suggests the presence of four hot loops (i.e., AB, AC, EF, and GF) that are seen in connection with the Hβ brightenings in the chromosphere. The two footpoints of the compact flaring loop AB, sheared on both sides of the neutral line, have been identified as sources of hard X-ray emission and coincide with Hα kernels (Takakura et al. 1994; Qiu et al. 1997). Together with magnetic and electric current evolutions, Wang et al. (1997) conjecture that the flare was triggered when a parasitic bipole continuously emerged from the region AB, and impacted at its top D on the overlying current-carrying loop EF. The portions of released energy were then transferred along the field lines passing through the initial flaring loop AB into other regions, and produced Hβ ribbons such as E, F and C in the chromosphere. However, the emission, seen at region P2 (Fig.5.7a), may be ascribed to the magnetic releasing of a local source. During the period 01:00UT-05:00UT, 7 small brightening events were observed appearing at this site, all showing up as an isolated X-ray bright point form, lasting about 2-11 minutes. Some examples are shown in Fig.5.8.

On the basis of the interpretations on 2D field topology in Sect.5.4.3, we deduce that the saddle points P1, P2 and P3, seen in Fig.5.7, give the location of possible nulls near the photosphere, and portions of the magnetic lane, such as P1C3, P2C3 and P3C5 that demarcate the neighboring L-class cells and pass through the saddles, depict the possible intersection of QSLs with the photosphere–we call those as 2D-QSLs. We find that most bright Hβ kernels tend to be involved with these structures; they are linked by the SXR bright loops or the underlying magnetic loops whose one footpoint related closely to the 2D-QSLs, e.g. at regions A and F.

Qiu et al. (1997) argued that a hot component of coronal plasma was found present above the footpoint A of the flaring loop AB, so the Hα line profiles in this region manifested the extra thermal feature in addition to having the nonthermal feature similarly in the footpoint B during the impulsive phase of the flare. We suggest that the associated strong thermal process above region A resulted from intermittent magnetic reconnection in the QSL between the loops AB and AC. At 02:47:55UT, 03:12:13UT, and 04:11:23UT, three other small brightening events occurred there (Fig.5.8d and e; Fig.5.7b), provide the complementary evidence. Coaligning the image at 03:12:13UT with that at 04:41:51UT, we identify the X-ray bright point, seen in Fig.5.8e, just located at region A between the two loops (labelled with '*'), seen in Fig.5.8f.

Another case of magnetic reconnection is inferred present at region G (Fig.5.8c), from a brightening event closely related with the QSLs. This event began at 02:33:11UT, and

remained until about 02:52UT; during the period, small brightening frequently haunted this region. In Fig.5.8c, we see the brightest emitting core (G) just located on the portion P2C3 of the 2D-QSLs, and a set of bright loops commonly in connection with this area. These facts suggest reconnection process in operating; its associated evaporation injected hot plasma into the field lines linking with region G to create the expanding SXR bright loops.

In particular, we notice that the isolated SXR bright point, seen in the flare (Fig.5.7a) and other small events (Fig.5.8a-e), is well coincided with the saddle P2. Its appearance and behavior seem to be shown having little connection with the bright emission in other areas. Such strange features in association with the null structure have been never found in the previous observations. We are thus uncertain of its origin due to magnetic reconnection in the null. The future work concerning local small-scale topology of this region may help us disclose its physics.

Our results agree with those of Parnell, Priest, and Golub (1994) as they show that X-ray bright loops can be considered as being reconnected magnetic loops, and also support the hypothesis that magnetic reconnection represents an elementary heating source, which can be at work in various coronal phenomena, ranging from small events to large-scale eruptions (Priest, Parnell, & Martin 1994; Mandrini et al. 1997).

In addition, we find the SXR loops in good agreement with the 2D field-line arrangement of the observed transverse field in the photosphere (Fig.5.7), which are nearly confined in the L-class cells, implying that they are supposed to be the low-lying coronal loops from the field modelling in Sect.5.4.3. Relying on shear estimations for these cells (in Sect.5.4.2) and the parameters Z_{top}/L_h and θ in Table 5-2, given by the force-free field models, we evaluate that the loops EF and AC, seen in Fig.5.7a, have the height of less than 11 Mm and 13 Mm, respectively, and the loop C3C6 has the height in the range 7-17 Mm above the photosphere. These analyses indicate that the energy release events in this active region took place in the low corona, and so corroborate physical significance of 2D field-line patterns to reveal the field topology in the low atmosphere, especially for the EFRs.

5.5 Summary

We have explored a 2D method to diagnose the topological properties of ARs, directly from the observed photospheric transverse field. This method, since not presuming any model as the representation of the field, thus allows us to approach a realistic field configuration with nonpotential character favoring the flare occurrence.

It is suggested that peculiar structures of the field near separatrics or separator are likely traced by virtue of some observational characters such as the arrangement of the chromospheric fibril or the photospheric transverse field, at least in some cases. When a null exists on the photosphere, the saddle point of photospheric transverse field gives the true position of a separator, and the magnetic lanes crossing at this saddle correspond to the intersection of separatrices. While, when a null is supposed beneath the photosphere, a field-line linkage is not strictly discontinuous at the saddle and so separator has low significance in this case; instead of the separatrices, the saddle and lanes are associated with the QSLs that also the preferable places for energy release.

We have indicated that the lowpass filtering is a key pretreatment of observed magnetograms for restoring their large-scale magnetic topology. This technique is efficient to reduce the disturbance of measurement noise on the determination of singular points deduced from

the Poincaré index, and make the 2D field-line patterns more clearly exhibited, which help demarcate 2D magnetic cells.

Applying the 2D method to the case of AR7321 (EFR), we have firstly obtained its 2D topology of observed transverse field. We find that a configuration of the observed field is topologically different from that of the computed field in the photosphere, for a constant-α model of the longitudinal field, and the magnetic cells of different origin have the different value of α. The results imply that for such an EFR its topological connectivities and certain features favorable to flare occurrence are involved with evolution of the magnetic structures. To confirm this supposition, we need to develop a more realistic model of the observed field (nonlinear force-free and/or time-dependent).

We have attempted a preliminary interpretation on the properties of 2D field topology. on the basis of a constant-α field model, we find that the shear can readily deform the magnetic lanes in location and shape, but hardly effect on the saddles, showing that the saddle positions are structural stable. Moreover, around these saddles the 3D field lines are manifested separating widely, showing up as 'cavity' structures, which infer the possible nulls present beneath the photosphere. Consequently, in this case the QSLs play the major role instead of the separator. We find that portions of the lanes are closely related to the intersection of QSLs with the photosphere, especially near the saddles; while other portions not correlated with QSLs have no general meaning of separatrices, but they distinctly separate two class of field-line connectivities of different height and shape. In the L-class cells, the projected 3D field lines are coincided with the alignments of photospheric transverse field (or the 2D field line patterns), corresponding to the underlying linkage for both the potential or nonpotential cases. Such features of the L-class cells are our physical basis of exploring the field topology in the low atmosphere, from 2D field-line patterns.

From the 2D observed field topology, we deduce the possible QSLs associated with the saddles and the portions of magnetic lane that demarcate the neighboring L-class cells. It is found that most bright Hβ kernels of the flare tend to be involved with these structures, linked by the SXR bright loops. Above one footpoint (A) of the flaring loop (AB), an extra thermal component of coronal plasma argued in Qiu et al. (1997) may result from magnetic reconnection in the QSL between two low-lying loops, which is also confirmed by other small brightening events in X-ray. In another event, a set of expanding hot loops are found commonly sharing a strongly emitting X-ray bright core in agreement with the possible QSLs, showing that reconnection precess is driven in that region and injects hot plasma into the related loops. The results obtained support the idea that reconnection is an elementary heating source, which is at work in various coronal phenomena, and prefers to the places involved with the topological singularity.

Figure Caption

Fig. 5.1. The photospheric vector magnetograms in the heliospheric plane, observed at (a) 01:44UT and (b) 04:12UT in NOAA 7321 on October 27, 1992. The longitudinal field (isocontours of $\pm$ 500, 1500, 2500 G) is drawn with solid and dashed lines for positive and negative values, respectively. The transverse field is represented with short arrows; the length gives the magnitude of the field and the arrow gives the direction. The longitudinal inversion line is plotted in thick lines. The field of view is $170'' \times 170''$.

Fig. 5.2. Determination of 2D topology of the observed field at 01:44UT, (a) for raw

field case and (b)-(d) for their filtered cases, with lowpass cutoff frequency $\bar{k}_c$=20, 10 and 5, respectively. The singular points computed with Poincaré index are marked with '◯' (I=1) or '◇' (I=-1). The 2D field lines are traced from the distribution of transverse field directions. In particular, the identified singular points of interest and their associated characteristic field lines are highlighted in thick plots. The small dashed-line boxes in (d) show the location of missed singular points due to an over-filtering. In each case the solid (dashed) contours show the longitudinal field.

Fig. 5.3. The 2D observed field topology in the photosphere, for two cases (a) at 01:44UT with the filter $\bar{k}_c$=10 and (b) at 04:12UT with the filter $\bar{k}_c$=20. '◯' gives the node points and '◇' gives the saddle points. The bold curves linking these singular points represent the magnetic lanes, which demarcate 2D magnetic cells of different field-line connectivities.

Fig. 5.4. The photospheric topology of computed transverse fields, derived from the observed longitudinal field at 01:44UT, on a constant α model (a) for the potential case (α=0) and (b)-(d) for the nonpotential cases, α=0.03, 0.06 and 0.09 respectively, in units of 0.69 Mm^{-1}.

Fig. 5.5. Top view of 3D field-line connectivity patterns as extrapolated from the longitudinal field on a constant-α model, (a) for α=0 and (b) for α=0.09 in unit of 0.69Mm^{-1}. The boldfaced field lines separating widely near the saddles divide the whole space into three regions (I, II and III), whose starting points depict the intersection of QSLs with the photosphere (the dashed lines). Some magnetic loops are numbered with Arabic numerals, whose photospheric foots are confined in L-class cells or which connect with H-class cells, to be further compared in Table 5-2. In the down left of (a), the arrow indicates the direction of side view for Fig.5.6(a-b).

Fig. 5.6. (a)-(b) Side view of the boldfaced field lines seen in Fig.5.5, for the two cases α=0 and α=0.09 in unit of 0.69Mm^{-1}. The direction of view point, ϕ, is 20^o with respect to y-axis (see the arrow in Fig.5.5(a)). (c)-(d) Side view of the numbered magnetic loops seen in Fig.5.5, for the two cases α=0 and α=0.09. The direction of view point is along y-axis.

Fig. 5.7. The coalignment of SXR images (gray map) at (a) 01:44:33UT, (b) 04:11:23UT taken by *Yohkoh* SXT from the filter Al.1 with the 2D topology of the observed transverse fields at 01:44UT and 04:12UT. '◯' gives the node points and '◇' gives the saddle points. The white curves linking these singular points represent the magnetic lanes. The 2D field-line patterns (black curves) are traced from the distribution of transverse field directions. In (a), the Hβ flare kernels (01:55:26UT) are plotted in thick black contours. The magnetic neutral line is drawn in white, dashed lines in both figures.

Fig. 5.8. The SXR images during 01:00UT-05:00UT taken by *Yohkoh* SXT from the filter Al.1. The field of view is $157'' \times 157''$.