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Evolution of the Photospheric Magnetic Field and Coronal Null Points before Solar Flares

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Abstract—Based on a topological model for the magnetic field of a solar active region (AR), we suggest a criterion for the existence of magnetic null points on the separators in the corona. With the problem of predicting solar flares in mind, we have revealed a model parameter whose decrease means that the AR evolves toward a major eruptive flare. We analyze the magnetic field evolution for AR 9077 within two days before the Bastille Day flare on July 14, 2000. The coronal conditions are shown to have become more favorable for magnetic reconnection, which led to a 3B/X5.7 eruptive flare.

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INTRODUCTION

The magnetic null points, i.e., the points at which all three field components become zero, are an important topological feature of solar active regions (ARs) (Syrovatskii 1962, 1969; Sweet 1969). The most favorable conditions for magnetic reconnection are created here (Somov 2006; McLaughlin 2008). There exist models for eruptive solar flares, such as the magnetic-flux *break-out* model, for which the presence of a null point in the AR corona is a key point (Antiochos 1998; Antiochos et al. 1999). The model of a fast *break* of a "new" magnetic flux through the "old" magnetic field of an AR in the corona (Syrovatskii and Somov 1980; Syrovatskii 1982) is basically similar. It is also important that, irrespective of the theories and models, currently available multiwavelength observations of the Sun are indicative of a possible relationship between eruptive events (major flares with the ejection of matter, eruptive prominences, coronal mass ejections) and magnetic null points in the corona (see, e.g., Aulanier et al. 2000).

According to Ugarte-Urra et al. (2007), 73% of the eruptive events occur in ARs with coronal null points. Another statistical analysis (Barnes 2007) also confirms that the presence of a coronal null point may be considered as an indicator of eruptive events. According the data of this author, such events are encountered almost three times more frequently in ARs with null points than in those without such points.

However, the quantitative results of the studies of the relationship between coronal null points and eruptive events by different authors differ greatly (for a discussion, see Barnes 2007). Some of the authors deny this relationship altogether (Li et al. 2006; Schmieder et al. 2007). The main reason is the lack of observational data on the coronal magnetic field. As a result, different authors use different techniques for extrapolating the magnetic field from the photosphere to the corona. Furthermore, when such an extrapolation has been performed, there are no reliable algorithms of searching for coronal null points (Barnes 2007). In this paper, we suggest a criterion for the existence of null points in ARs based on the topological model that has previously proven efficient in describing major solar flares (Oreshina et al. 2004; Oreshina and Somov 2006a, 2006b).

Magnetic reconnection can also take place outside null points on peculiar field lines called separators. The field structure in the plane perpendicular to the separator is the same as that near a 2D null point. Basically, the separator differs only in that it has a longitudinal magnetic field component. Of course, the latter does not forbid the reconnection process, but the longitudinal field can limit significantly the intensity of energy release in a reconnecting current sheet on a separator (Somov and Titov 1985). In this paper, we show that there exists a parameter of the topological model for the AR field that allows the longitudinal magnetic field on a separator, i.e., the magnetic reconnection conditions, to be judged.

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SEARCHING FOR CORONAL NULL POINTS

Gorbachev et al. (1988) studied the topological features of a "dipole-type" field, i.e., a model magnetic field produced by two positive and two negative point sources, "charges," whose sum is zero. The charges lie in the same plane. A null point was shown to emerge on a separator at certain relative positions of the charges. A criterion for the existence of such a point was suggested.

Furthermore, it was shown that even small changes near the critical configuration of the magnetic charges can give rise to a null point on a separator and to its rapid motion along the separator. Therefore, in general, the evolution of an AR can lead to such a critical field configuration that even small sunspot displacements or small magnetic-flux variations in sunspots will cause a sharp decrease in the longitudinal magnetic field on the separator and, hence, a sharp increase in the rate of reconnection on it, i.e., a flare.

The goal of this paper is to extend the range of applicability of the previously suggested criterion to the actual conditions in ARs whose modeling often requires introducing an odd number of charges, such that their sum is nonzero.

The method suggested by Gorbachev et al. (1988) consists in analyzing the magnetic field in the plane of the charges. Two null points exist in this plane for the cases considered. One separates the fluxes of two positive charges, while the other separates the fluxes of two negative charges. These points are the separator footpoints. One of the characteristics of the null point $\mathbf{r}_0$ is the topological index

$$I_{\text{top}}(\mathbf{r}_0) = \operatorname{sgn}\det M(\mathbf{r}_0) = \operatorname{sgn}(\lambda_1\lambda_2\lambda_3).$$

Here, $M(\mathbf{r}_0)$ is a matrix with elements

$$M_{\alpha\beta} = -\frac{\partial^2\psi}{\partial r_\alpha \partial r_\beta},$$

ψ is the field potential; λ_1, λ_2, and λ_3 are the eigenvalues of the matrix.

Gorbachev et al. (1988) showed that when a third null point exists on the separator, the indices I_{top} at both its footpoints has the same sgn.

To generalize this conclusion, we will use the following analogy. If the velocity vector $\mathbf{v}$ is substituted for the vector $\mathbf{B}$ in the formula

$$\mathbf{B}(x,y,z) = \sum_{i=1}^{N} \frac{e_i}{|\mathbf{r}-\mathbf{r}_i|^2}\frac{\mathbf{r}-\mathbf{r}_i}{|\mathbf{r}-\mathbf{r}_i|}, \qquad (1)$$

describing the AR magnetic field, then we will obtain the velocity field of an ideal incompressible fluid produced by N sources and sinks e_i located at points $\mathbf{r}_i$ (see Sedov 1976, Ch. 2, Sect. 3 and Ch. 8, Sect. 11; Molodenskii and Syrovatskii 1977). Such a motion is potential and described by the equations

$$\operatorname{curl}\mathbf{v} = 0, \qquad \operatorname{div}\mathbf{v} = 0,$$

i.e., the same equations as those for a potential magnetic field. They are valid everywhere outside the field sources.

Denote the eigenvectors of the matrix M that correspond to the eigenvalues λ_1, λ_2, and λ_3 at point $\mathbf{r}_0$ by $\mathbf{R}_1$, $\mathbf{R}_2$, and $\mathbf{R}_3$. By analogy with a fluid flow, it can be said that the fluid "flows into the point along $\mathbf{R}_k$" if $\lambda_k < 0$ and "flows out from the point along this vector" if $\lambda_k > 0$. Note that the null points are neither the sources nor the sinks and the entire fluid that "flowed into the point" (or, more precisely, into the neighborhood of the null point, since the velocity at the null point itself is zero by definition) along one of the principal directions "flows out from it" along different directions.

Of course, each line of the velocity field starts in a source and ends in a sink. In other words, talking about the separator and its footpoints, we have in mind not the entire field line separating different fluxes but only the part of it that lies above the plane of the charges. As a field line, the separator is a streamline in hydrodynamic terms, i.e., a velocity field line. Note also that the only points of the separator lying in the plane of the charges are its footpoints, null points. Consequently, there are no sources and sinks everywhere along the separator (see also Fig. 1a). This means that the fluid flows along the separator and cannot accumulate or disappear at its particular location. Thus, if the eigenvalues $\lambda_z > 0$ at both separator footpoints, then the fluid flows out from these points upward along the separator toward each other. In this case, a point should exist on the streamline at which the flows are encountered, i.e., a null point (Fig. 1b). Similarly, if $\lambda_z < 0$ at both separator footpoints, then a point should exist on the separator at which the flow splits up, streaming down toward the separator footpoints, i.e., a null point.

Thus, the criterion for the existence of a null point on the separator above the plane of the charges is the condition

$$i_{\text{sep}} = \operatorname{sgn}(\lambda_z(\mathbf{r}_1)\lambda_z(\mathbf{r}_2)) > 0, \qquad (2)$$

where $\mathbf{r_1}$ and $\mathbf{r_2}$ are the null points at the separator footpoints. This conclusion does not depend on the balance and parity of the field sources. It is only necessary that the pair of null points be the footpoints of this separator.

If $i_{\text{sep}} < 0$, then the fluid that flows out from the sources flows in the plane of the charges (and, of course, in its vicinity) toward one of the separator footpoints, i.e., a null point. Here, it changes the direction of its motion near the null point: it flows initially upward, subsequently again along the separator, and finally flows down at the other separator footpoint (near the second null point). The fluid flow is then directed toward the sinks. All these changes in the velocity field structure are schematically shown in Fig. 1a. The equality $i_{\rm sep} = 0$ means that there is no flow along the z axis at least at one separator footpoint and the entire flow in the vicinity of this point spreads in the xy plane. This is the time when a third null point appears, which will "run" along the separator as the charges move further. If $\lambda_z = 0$ at both footpoints of the separator, then it is a null line, ideal conditions for magnetic reconnection.

Generally, the longitudinal magnetic field $\mathbf{B}_{||}$ always dominates near the separator, since the transverse magnetic field $\mathbf{B}_{\perp}$ disappears on the separator. The transverse field components are reconnected on the separator, thereby being actively involved in the change of the magnetic field topology. Reconnection in a current sheet on the separator conserves the longitudinal field flux (see Somov 2006). As a result, we get the impression that the longitudinal field generally plays only a passive role in the topological aspect of reconnection. However, it affects the physical properties of the reconnecting current sheet. The longitudinal field reduces the plasma compressibility. As a result, the current sheet becomes thicker and the reconnection rate decreases. If, for some reason, the longitudinal field on the separator decreases, then the reconnection rate increases. This is a physical prerequisite for the "topological trigger" related to the longitudinal magnetic field on the separator (Gorbachev et al. 1988). Another thing is also fundamentally important. The topological trigger of a flare is a rapid change in the topology of the large-scale magnetic field of an AR (Somov 2008). This effect is illustrated by Fig. 1. The directions of the magnetic fluxes in the AR change abruptly from the very beginning of the topological trigger. During this process, the separatrix surface related to the null point $X3$ running along the separator rapidly "turns" the large-scale magnetic field of the AR like a page in a book. It is not surprising that this process generates a major eruptive flare.

Meanwhile, Li et al. (2006), Barnes (2007), and Schmieder et al. (2007) showed that the existence of a coronal null point does not always lead to a flare. The advantage of our method is that it allows the null points to be found on separators, i.e., at the locations where the magnetic energy is accumulated before a flare, which is then converted into the energy of the plasma and accelerated particles via magnetic reconnection.

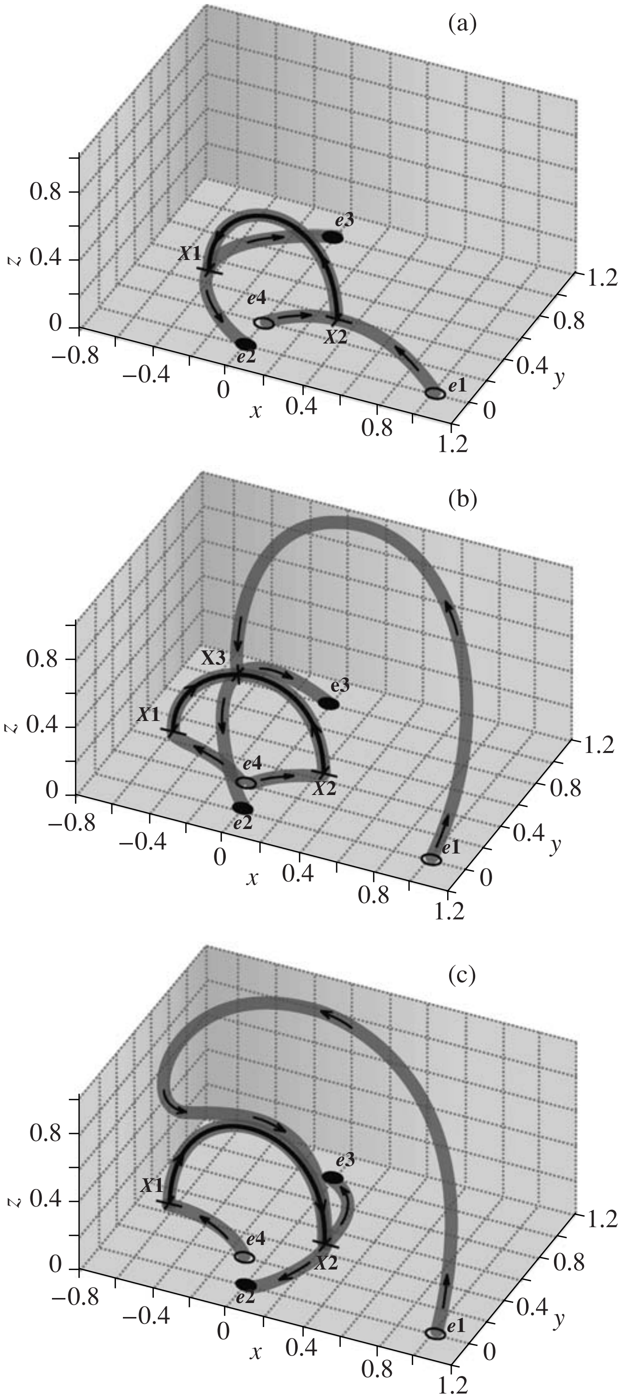

Fig. 1. Magnetic field structure near the separator at various relative positions of four charges $e1$, $e2$, $e3$, and $e4$ (the values and coordinates of the charges were taken from Gorbachev et al. (1988)). $X1$ and $X2$ are the magnetic null points in the plane of the charges. The black line connecting them is the separator. (a) The magnetic field along the separator is directed from point $X2$ to point $X1$; there are no coronal null points. (b) A null point $X3$ exists on the separator. The magnetic field at both separator footpoints is directed upward. (c) The magnetic field along the separator is directed from point $X1$ to point $X2$. There are no coronal null points.

Table 1. Values and coordinates of the charges used to model AR 9077

Polarity	$e_i, 10^4$	x_i	y_i	z_i	Polarity	$e_i, 10^4$	x_i	y_i	z_i
July 12					July 14				
n_1	19	82	53	−9	n_1	17	90	53	−9
n_2	13	60	53	−9	n_2	18	60	53	−9
s_1	−22	130	55	−9	s_1	−9	130	55	−9
s_2	−27	72	30	−9	s_2	−19	79	27	−9
s_3	−16	15	45	−9	s_3	−15	15	50	−9

Let us consider the physical meaning of the parameter λ_z. In principal axes,

$$\lambda_z = M_{zz} = -\frac{\partial^2 \psi}{\partial z^2} = \frac{\partial B_z}{\partial z}. \qquad (3)$$

The lower the value of λ_z, the slower the increase in the field strength along the separator, and the lower values it reaches and, hence, the better the conditions for reconnection. Thus, the parameter λ_z of the photospheric magnetic field can be used to evaluate the conditions for coronal reconnection. If the photospheric field of an AR changes with time in such a way that this parameter decreases, then it may be concluded that the AR evolves toward a flare. Let us demonstrate the efficiency of the method using the Bastille Day flare as an example.

EVOLUTION OF AR 9077 BEFORE THE JULY 14, 2000 FLARE

AR NOAA 9077, in which the Bastille Day flare occurred, was observed for several days before and after this event by almost all ground-based and space-borne instruments (Solar Physics, Vol. 204, 2001). More than one hundred flares, including three X-class flares, were detected in the AR over this period. The largest (X5.7) flare was observed on July 14 (Bastille Day one) and the next largest flare was observed on July 12. As was suggested by Somov et al. (2002), the AR possessed a magnetic energy after this flare that was insufficient for a major flare and, accordingly, accumulated it for two days (from July 12 to July 14).

Somov et al. (2004, 2008) constructed a theoretical model for this AR. They showed that the energy release could be explained by reconnections on two separators: one connects the null points X_1 and X_2, while the other connects the null points X_1 and X_3 in the plane of the charges (Fig. 2).

MDI/SOHO magnetograms were taken as the initial data. Berger and Lites (2003) showed that the MDI instrument systematically underestimated the actual data on the field. The following calibration should be performed to obtain reliable values: the MDI values below and above 1900 G in magnitude should be multiplied by 1.45 and 1.9, respectively. Figure 2a presents the magnetograms constructed by using the corrected values.

The characteristic feature of this AR is a w-shaped photospheric neutral line indicated by the thick line in the figure. The five largest concentration centers of the magnetic fields can be distinguished: two of north polarity (n_1 and n_2) and three of south polarity (s_1, s_2, and s_3). The magnetogram is satisfactorily fitted by a field of the form (1), where the charges and radius vectors are presented in Table 1. The x axis is directed from east to west, the y axis is directed from south to north, and the z axis is directed away from the solar center perpendicularly to the solar surface. The $z = 0$ plane corresponds to the photosphere. The charges that produce the field under study are located beneath the photosphere at the $z = -9$ level.

Figure 2b presents model magnetograms, i.e., isolines of the line-of-sight (l) field component in the $z = 0$ plane. The l field component was calculated as follows:

$$\mathbf{B}_l = -B_x \sin\varphi \qquad (4)$$
$$- B_y \cos\varphi \sin\theta + B_z \cos\varphi \cos\theta,$$

where θ is the AR latitude measured from the equator northward and φ is the longitude measured from the central meridian westward. The model magnetograms also show the same isolines as those on the MDI magnetograms.

The 3D structure of the field above the photospheric plane was calculated by integrating the system of ordinary differential equations

$$\frac{\mathrm{d}x}{B_x} = \frac{\mathrm{d}y}{B_y} = \frac{\mathrm{d}z}{B_z},$$

Table 2. Indices λ_z at the separator footpoints

Parameter	July 12	July 14
X_1	209.6	90.7
X_2	−6.3	−2.4
X_3	−8.8	−1.8

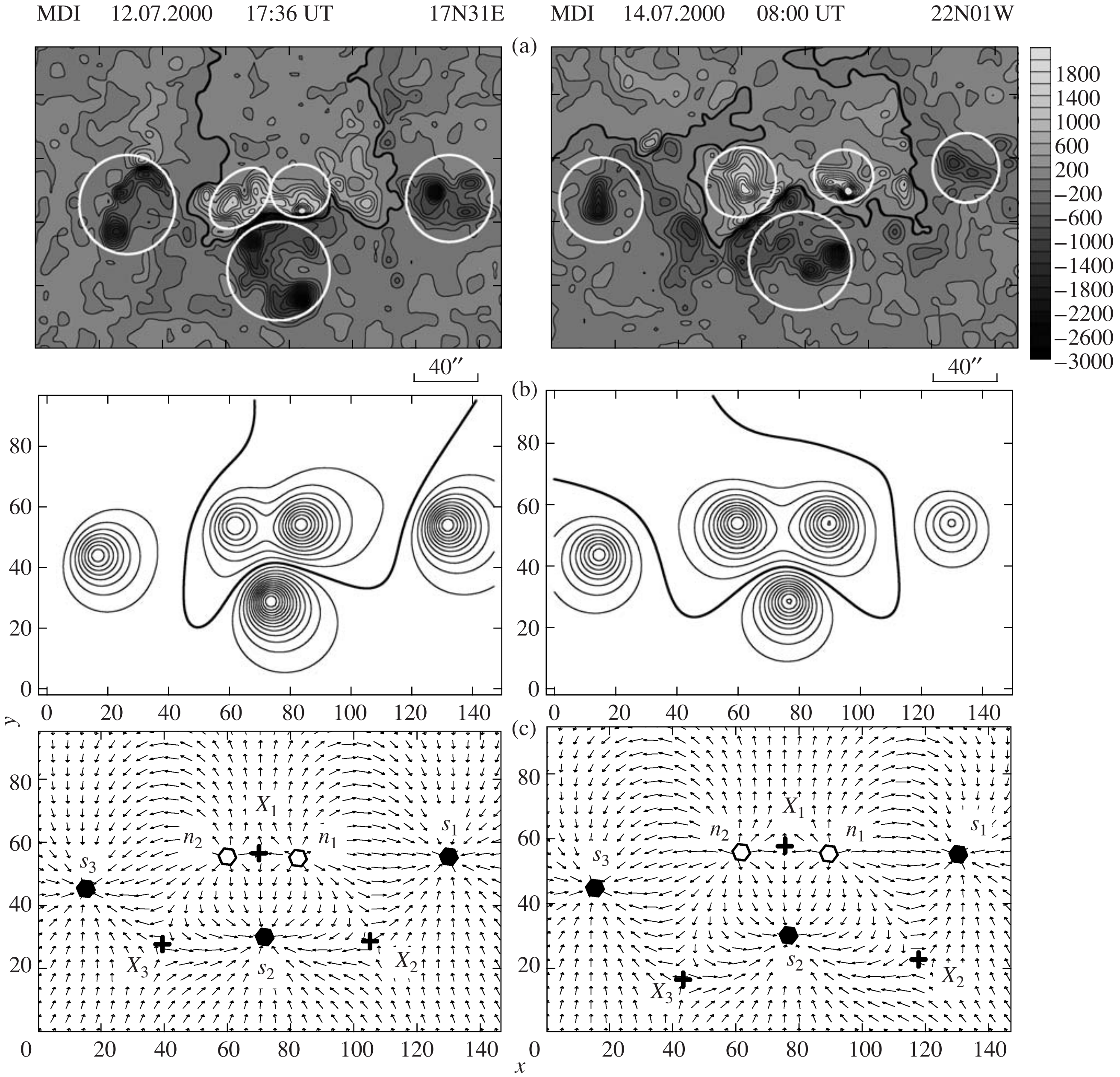

Fig. 2. (a) MDI/SOHO magnetograms for AR NOAA 9077; the magnetic field strength on the isolines is shown in G. (b) Model magnetograms for the same AR with the same isolines. (c) Vector field in the plane of the charges: n_1 and n_2 are the north-polarity charges; s_1, s_2, and s_3 are the south-polarity charges, and X_1, X_2, and X_3 are the null points.

where (dx, dy, dz) is the element taken along the field line.

Based on the presented model, let us consider how the indices λ_z changed at the points X_1, X_2, and X_3 from July 12 to July 14. The results of our calculations are presented in Table 2. Applying criterion (2) to the data in Table 2, we will find that $i_{\text{sep}} < 0$ at the footpoints of both separators. This suggests that there are no coronal null points. However, the absolute values of the indices λ_z decreased on both separators. Therefore, the AR evolved toward the formation of null points on the separators and the conditions for reconnection became increasingly favorable. Indeed, let us consider the variations in magnetic field strength along the eastern separator, i.e., the separator connecting the points X_1 and X_3 as an example (Fig. 3). The solid and dashed lines indicate the values for July 12 and 14, respectively. We see that the field on the separator decreased significantly: whereas on July 12 the maximum strength exceeded 900 G, on

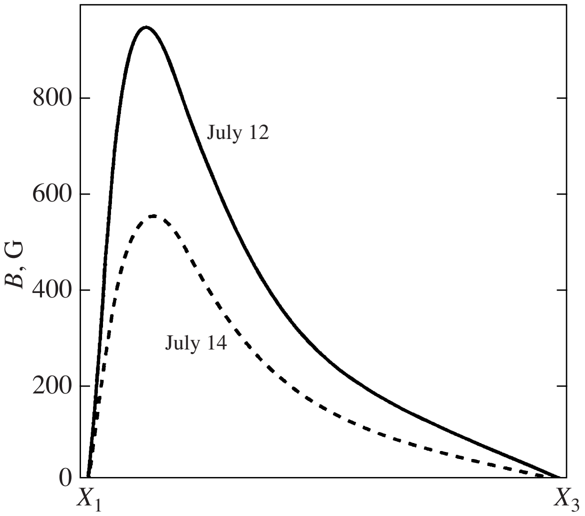

Fig. 3. Variation in the magnetic field strength along the eastern separator on July 12 (solid curve) and July 14 (dashed curve).

July 14 it did not reach even 600 G. Consequently, the conditions for reconnection became more favorable. All of the aforesaid is also valid for the western separator, on which the pattern of field variations is similar to that in Fig. 3.

Thus, the slow photospheric motions and the photospheric magnetic field variations observed in AR NOAA 9077 from July 12 to July 14, on the one hand, allowed the magnetic energy to be accumulated and, on the other hand, led to an improvement in the conditions for magnetic reconnection on both separators. It may be concluded that the magnetic field structure evolved toward a flare that occurred on July 14, 2000.

CONCLUSIONS

Based on a topological model for the magnetic field of ARs, we suggested a criterion for the existence of null points on separators in the solar corona. Such points are known to be an important topological feature of ARs; the conditions for reconnection in solar flares are most favorable at them. This is a physical prerequisite for the "topological trigger" related to the longitudinal field on a separator (Gorbachev et al. 1988). However, another thing is also fundamentally important. The topological trigger of a flare is a rapid change in the topology of the large-scale magnetic field of an AR (Somov 2008). The existence of coronal null points plays a key role in a number of models for eruptive events. We showed that the separatrix surface related to the null point running along the separator rapidly "turns" the AR large-scale field like a page in a book. It is not surprising that this process generates a major eruptive flare.

The suggested method for analyzing the topology of the large-scale magnetic field of an AR allows the coronal null points to be found on separators, i.e., precisely where the magnetic energy is accumulated before a flare and is converted into the particle energy during a flare. We showed that there exists a topological model parameter that allows the longitudinal magnetic field on a separator, i.e., the conditions for magnetic reconnection, to be judged. This parameter is the eigenvalue λ_z at the separator footpoints. The lower its value, the better the conditions for magnetic reconnection. As an example, we considered the evolution of AR NOAA 9077 two days before the Bastille Day flare. No coronal null points were found in this AR. However, we showed that the coronal conditions for reconnection on both separators before the flare improved significantly, which led to an X5.7 eruptive flare.

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