The Magnetic Field Distribution in Active Regions in the Quiet Time and during Large Solar Flares

I. M. Podgorny [1], A. Podgorny [1,2], N. S.Meshalkina [3]

[1]Institute for Astronomy RAS, Moscow, Russia
[2]Lebedev Physical Institute RAS, Moscow, Russia
[3]Institute of Solar-Terrestrial Physics RAS, Irkutsk, Russia

E mail (podgorny@inasan.ru)

Accepted : March 14, 2014

Abstract. Many controversial results about magnetic field behavior in active regions during solar flares are published. The magnetic field dynamics of active regions that produce large (X-class) flares are investigated in this paper. The magnetic flux is obtained by using the results of calculations of the normal magnetic component in the active region. It is shown that the main condition for appearance of an X-class flare is the big magnetic flux ($\Phi > 10^{22}$ Mx) of active region. This condition is necessary but not a sufficient. The large flare appears above an active region, if the magnetic field distribution is very complex. A simple active region with the bipolar magnetic field distribution does not produce a flare. There are no singular magnetic lines above a bipolar region, which can be responsible for a current sheet creation before the flare. During a solar flare, when the accumulated energy is fast released, the conservation of the magnetic field distribution in the active region during the majority of flares takes place. This surprising fact follows from the analysis of the array data obtained with the SOHO and SDO spacecrafts. The presented results support the flare theory based on the slow magnetic energy accumulation in the coronal current sheet before a flare and its explosive realize due to current sheet instability. The scheme of the current sheet creation is discussed, which explains the magnetic field dissipation in the corona without perturbations of magnetic field distribution on the Sun surface during a flare.

Keywords: sun, solar flare, active region, magnetic flux

Introduction

The 3D MHD numerical simulations show that a current sheet is created in the corona before a flare due to disturbances arrived from the photosphere (Bilenko et al., 2002; Podgorny et al., 2008; Podgorny and Podgorny, 2008; Podgorny and Podgorny, 2012a; 2012b). These simulations are carried out for initial and boundary conditions obtained from photospheric measurements before a flare. The currents are concentrated at high altitude in the vicinity of an X-type singular magnetic line above the active region. The current sheet can be formed only at a complex field distribution in an active region, when the singular magnetic line exists in the corona above an active region. If the flare mechanism is based on current sheet decay, the flare production active region must have a complex field distribution (type βγδ). β means existence of the magnetic inversion line in the active region, γ means a complex form a field inversion line (or lines), and δ means that magnetic sources of one polarity are intruded in the field of another polarity.

The initial and boundary conditions on the photosphere in the 3D MHD numerical simulation are set using the line-of-sight magnetic maps obtained by SDO and SOHO space craft measurements. The normal and tangential components on the photosphere are calculated in the potential approximation of the magnetic field distribution (Podgorny and Podgorny, 2013). The full system of 3D MHD equations with all dissipative terms is taken into account in these numerical experiments. No assumptions about the mechanism of the flare are introduced in calculations. It is shown that the energy is accumulated in the current sheet magnetic field before the flare, and explosive energy release takes place at the current sheet decay due to fast magnetic reconnection (Podgorny, 1989). The amount of the accumulated magnetic energy (10^{32} erg) is sufficient to produce a flare and coronal mass ejection. The calculated position of the current sheet for the flare is coincided with the position of the radio source in the flare (Podgorny et al., 2008). The results of the numerical 3D MHD simulation (Podgorny and Podgorny, 2012a; 2012b) permit to construct the solar flare electrodynamical model, which explains all the main observational data, obtained on spacecrafts Yohkoh and RHESSI (Masuda, et al., 1994; Lin, et al., 2003). It is also shown that flare relativistic protons are accelerated in the Lorenz electric field along the magnetic X-type line (Podgorny et al., 2010).

The explosive destruction of the current sheet during a flare that appears in the corona at the high altitude should not produce magnetic flux change of an active region. Therefore, the flare may not have an impact on the magnetic field evolution in the active region. Due to short flare duration (order of 10 min) compared to the duration of the active region magnetic field evolution before the flare (about 5 days), the probability of occasional the photospheric magnetic field disturbance appearing during the flare is low. So, magnetic field distribution in active regions should not change during the appearance of most of the observed flares. Attempts to detect disturbances of the active region magnetic field responsible for a flare which carried out in several works are very controversial (Jiang et al., 2012; Leka, Bames, 2007; Masuda, et al., 1994; Petrie, Sudol, 2010; Sun, et al., 2012; Wang et al., 2009; Wan et al., 2011). Petrie (2013) reports that the magnetic flux order of 10^{20} Mx has been concentrated near the magnetic reverse line of AR NOAA 11158 at the X2.2 flare. Our primary publications (Podgorny and Podgorny, 2011; 2013) do not reveal the strong photospheric disturbances during the flare, which could explain the energy released during a flare order of ~ 10^{32} erg. In this paper we present new data showing that the necessary condition for large (class X) flares appearance is existence of the big magnetic flux and complexity of the magnetic field distribution in an active region. The flare appearance is not accompanied by magnetic field disturbances in the active region.

Flare Production Dependence on the Active Region Magnetic Flux

The SOHO MDI http://soi.stanford.edu/magnetic/index5.htm and SDO HMI http://jsoc.stanford.edu/ajax/lookdata.html magnetograms present the photospheric magnetic field component directed along the line-of-sight. These magnetogramms provide only qualitative estimation of the magnetic flux dynamics, since the measured magnetic field line-of-sight component depends on the active region position on the solar disk. For magnetic flux calculation it is necessary to obtain distribution of the normal magnetic component on the photosphere. The normal magnetic field component distribution in the active region is calculated using the distribution of line-of-sight data. The calculation is performed in the potential approximation (Podgorny and Podgorny, 2011), which is possible, if the magnetic field on the photosphere is defined mainly by currents under the photosphere but not by the currents in corona. The current sheet must be situated high in the corona. The Laplace equation with oblique derivative as the boundary condition on the photosphere has been solved to obtain magnetic configuration above an active region in the potential approximation. The system of equations for the magnetic potential φ is solved numerically

$$\Delta\varphi = 0;\ \partial\varphi/\partial l_{PhBoun} = -B_{ls};\ \mathbf{B} = -\nabla\varphi. \qquad (1)$$

The SOHO MDI and SDO HMI magnetic maps are used to specify the boundary conditions on the photosphere. The line-of-sight component Bls can be written as the magnetic potential derivative along the line-of-sight $B_{ls} = -\partial\varphi/\partial l$ on the photosphere.

For a sufficiently big computational domain the boundary conditions at the nonphotospheric boundary do not play a decisive role. The field is weak on this boundary and should not affect the solution appreciably. Two methods are specified for setting the boundary conditions on the nonphotospheric boundary.

1. The normal magnetic field component on the entire nonphotospheric boundary B_{NPhB} is specified to be constant. The normal to the boundary component is calculated from the condition of the zero total magnetic flux across the entire boundary of the computational domain (incoming and outgoing fluxes are equal).

2. The magnetic potential is specified to be zero at the nonphotospheric boundary.

The results of calculations show that the difference between solutions with these boundary conditions is insignificant. The size of the photospheric boundary of the computational domain considerably exceeded the size of the active region, so that the weak field at active region boundaries could not influence the results of potential field calculations considerably (Podgorny and Podgorny, 2008).

The time dependences of the magnetic flux of the typical active regions, which produce X-type flares, are shown in Figure 1. All registered large flares have appeared at the magnetic flux exceeding 10^{22} Mx. The moments of time of flare appearance are shown by arrows. The NOAA 10486 active region (Figure 1a) is appeared on the eastern limb October, 23 2005 with the big magnetic flux and produced the flare X5.4. The exact calculation of the active region magnetic field distribution near the limb is impossible. The magnetic flux is estimated as $\Phi > 10^{22}$ Mx.

Figures 1b - 1d show typical examples of the magnetic flux dynamics of the active regions that produce flares. Here, selected the active regions that appeared on the visible solar disk and produced large flares. All observed flares appear after magnetic flux increasing. The usual time of big active region development is order of 3 - 5 days. There is a clear pattern – all large flares occur above the active region with the magnetic flux bigger than $\Phi = 10^{22}$ Mx. Some flares occur at the equal northern and southern magnetic fluxes, but other flares are observed with an unbalanced large magnetic flux. The flares can start at increasing and decreasing the magnetic flux, as well as at the unchangeable flux for a few hours. The only condition for the appearance of the flares shown in Figure 1 cases is the big magnetic flux ($\Phi \geq 10^{22}$ Mx). However, the condition $\Phi > 10^{22}$ Mx is necessary one, but not a sufficient. All active regions which produce the large flares (including the regions for which magnetic flux evolutions are presented in Figure 1) have very complex magnetic field distribution. There are many active regions with big magnetic flux, which produce no large flares. The simple bipolar flares do not produce any flares. Figure 2 shows the magnetograms of two active regions. One of them NOAA 10720 is very complex. It has produced four flares of class X and about 30 flares of class C and class B flares, but the region NOAA 11072 produces no flares. The active region NOAA 11072 has a bipolar field distribution with leading and following solar spots of different polarity separated by a simple magnetic inversion line. The magnetic field lines above this region have the form of loops. There are no X-type singular lines in such configuration of the magnetic lines.

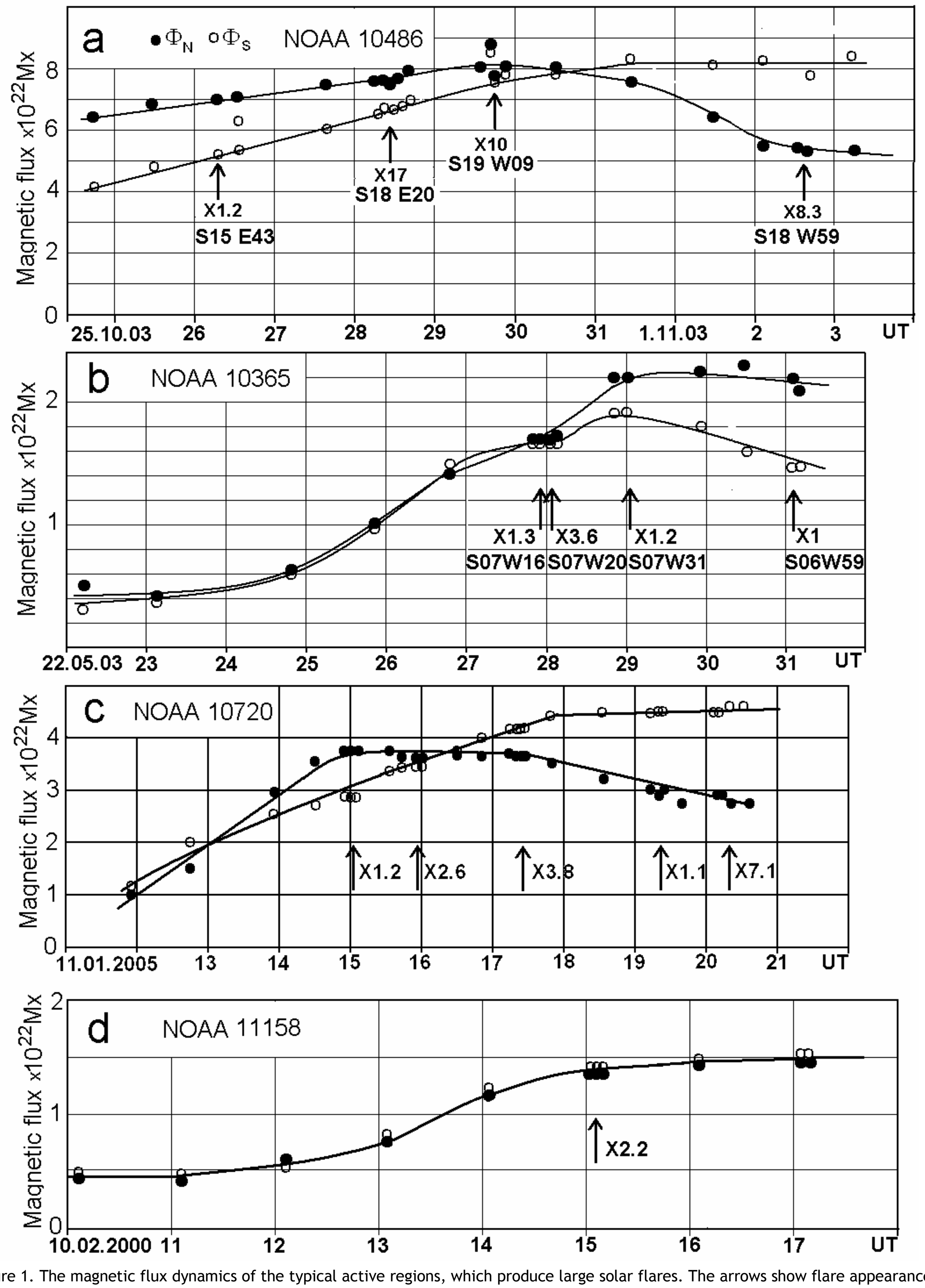

Figure 1. The magnetic flux dynamics of the typical active regions, which produce large solar flares. The arrows show flare appearance.

For a current sheet creation it is necessary to have a singular line in the vicinity of which a current sheet can be formed and free magnetic energy accumulation for a flare can take place.

The active region NOAA 10720 with a complicated distribution of the magnetic field and the line inversion of the magnetic field of complex shape has caused many big solar flares. In such a complex configuration of the photospheric field the singular lines can exist above the active region. All active regions analyzed in Figure 1 have also the very complex magnetic distribution. These regions have a complex shape of the magnetic inversion line, and magnetic sources of one polarity are embedded in field sources of other polarity. But, the simple bipolar active regions produce no flares. Thus, the second condition of flare appearance is a complex configuration of the field distribution in the active region.

The important role of magnetic field complexity for flare production is seen in Figure 3, where GOES X-ray, the magnetic flux time dependence, and magnetograms are presented for the active region NOAA 10656 that has initiated on the back side of the Sun. It has appeared on the eastern limb on August 7, 2004 with the northern and southern magnetic fluxes bigger than 10^{22} Mx. The active region NOAA 10656 with a magnetic flux up to 4×10^{22} Mx produces no large flares (class X) during several days, when it moves on the solar disk. Until 11.08.2004 the active region NOAA 10656 magnetograms show two compact groups of field sources of northern and southern polarity. The magnetic sources of one polarity are clearly separated by the single inversion line from sources of other polarity. Such a bipolar distribution of field sources in the active region forms magnetic loops in the corona, but a singular magnetic field line cannot be formed.

During increasing of magnetic flux up to ~3×1022 Mx the active region NOAA 10656 magnetic configuration does not reveal high magnetic field complexity. Despite of the big northern and southern magnetic fluxes, the active region NOAA 10656 does not produce any large flares until August 13. The value of solar flares that have been produced by the region NOAA 10656 before August 13 is not exceeding the C class. Since August 11 the field distribution distribution complexity increases. The configuration of the magnetic field is changed: the sources of the one polarity are embedded in the field of other polarity, and the field inversion line has got a rather complicated form. The field distribution becomes βγδ type. Increasing of flare activity with the increasing of the field distribution complexity in the active region is clearly seen. X1 flare appears on August 13 above the active region with the high complexity of magnetic field distribution. The flare of class X1 appears, when the magnetic flux becomes ~4×10^{22} Mx. Then a series of flares of class M are observed on August 14 and 15. From comparison of magnetic flux time dependence and the magnetograms shown in Figure 3 one can conclude that flare activity demands not only the big magnetic flux of the active region, but also the complexity of magnetic field distribution.

Apparently, the magnetic field configuration above the active region NOAA 10656 contains the X-type singular lines. A current sheet formation in the corona occurs in the singular line vicinity (Podgorny and Podgorny, 2012a; 2012b). Apparently, the current sheet is located at the high latitude. Decay of such a current sheet cannot produce noticeable disturbances of the active region magnetic field (Figure 1).

The Magnetic Field Distribution Conservation in the Active Region during Flares

It is has been declared in (Podgorny and Podgorny, 2011; 2013) that the magnetic flux of the active region remains unchangeable even during large flares. This conclusion seems contradicts the fact that the source of the flare energy is the Sun. However, the visual analysis of photographs of the magnetograms and magnetic field distributions in the active regions during the flares does not show any changes of the magnetic field distribution in an active region that could be associated with flare appearance. Only at the giant flare X17 on October 28, 2003 in the active region NOAA 10486 a narrow maximum of ~ 1000 G has been registered (Podgorny and Podgorny, 2011), but this maximum does not cause a noticeable change in the magnetic flux of the active region. The magnetic flux during this flare is remained constant to within 1%.

The comparison of the magnetic field distributions measured on February 15, 2011 in NOAA 11158 near the X2.2 flare maximum is presented in Figure 4. The time intervals between magnrtogram measured with the SDO space observatory are taken 90 s and 16 min. The half-width of X-ray flare pulse is ~ 20 min. Figure 4 shows the distribution of the magnetic fields at three time moments around the flare maximum (1:44:15, 1:45:45 and 2:00:00) and the difference of these distributions. It is clearly seen the preservation of magnetic field distribution during the flare. The northern and southern magnetic fluxes of the active regions remain constant to within 1%. The position of this flare in the active region is S20 W10. The angle between the line-of-sight measurements and the normal to the Sun surface is about 22°. Highly constancy of the distribution of the line-of-sight magnetic field component shows that at the maximum energy release of the X2.2 flare on February 15, 2011 the normal magnetic field component and the tangential component remain also constant. This means that the energy of the magnetic field, which explosively released during the flare, is not supplied from the Sun during a flare, but the energy for a flare is accumulated in the corona in the pre-flare time. The energy for a flare can be accumulated in the magnetic field a current system (current sheet) above the active region. Such possibility is demonstrated in MHD numerical simulations (Bilenko et al., 2002; Podgorny and Podgorny, 2012a; 2012b).

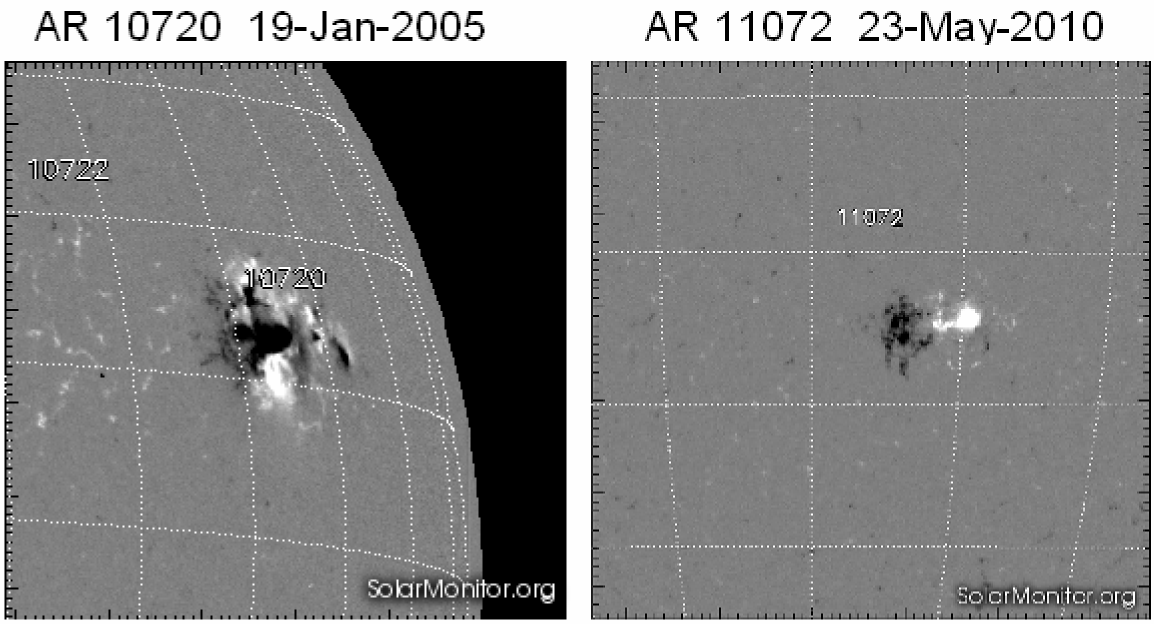

Figure 2. The active region NOAA 10720 magnetogram with a complex field distribution, causing many strong flares, and the active region NOAA 11072 magnetogram with bipolar field distribution, which produces no flares.

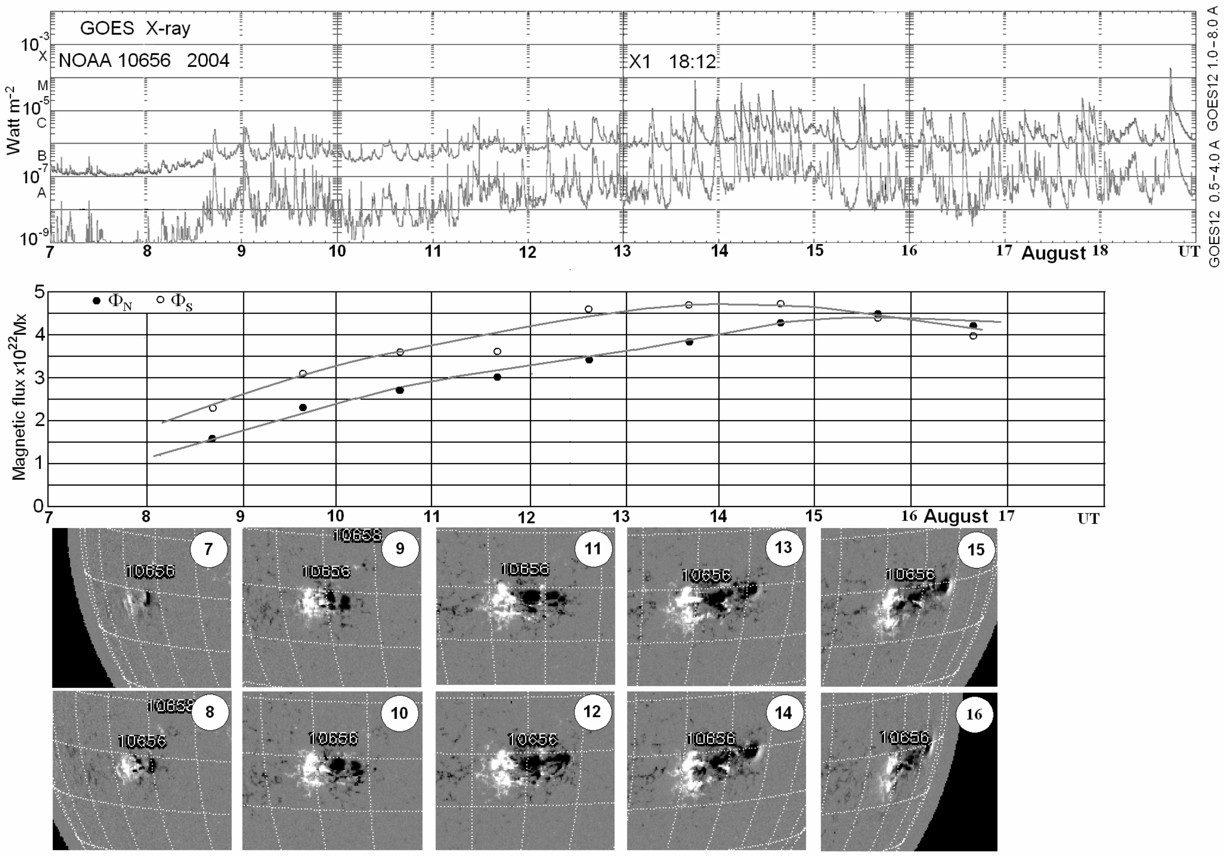

Figure 3. The X-ray emission according to GOES, magnetic flux, and the active region NOAA 10656 magnetograms from 7 to 17 August 2004.

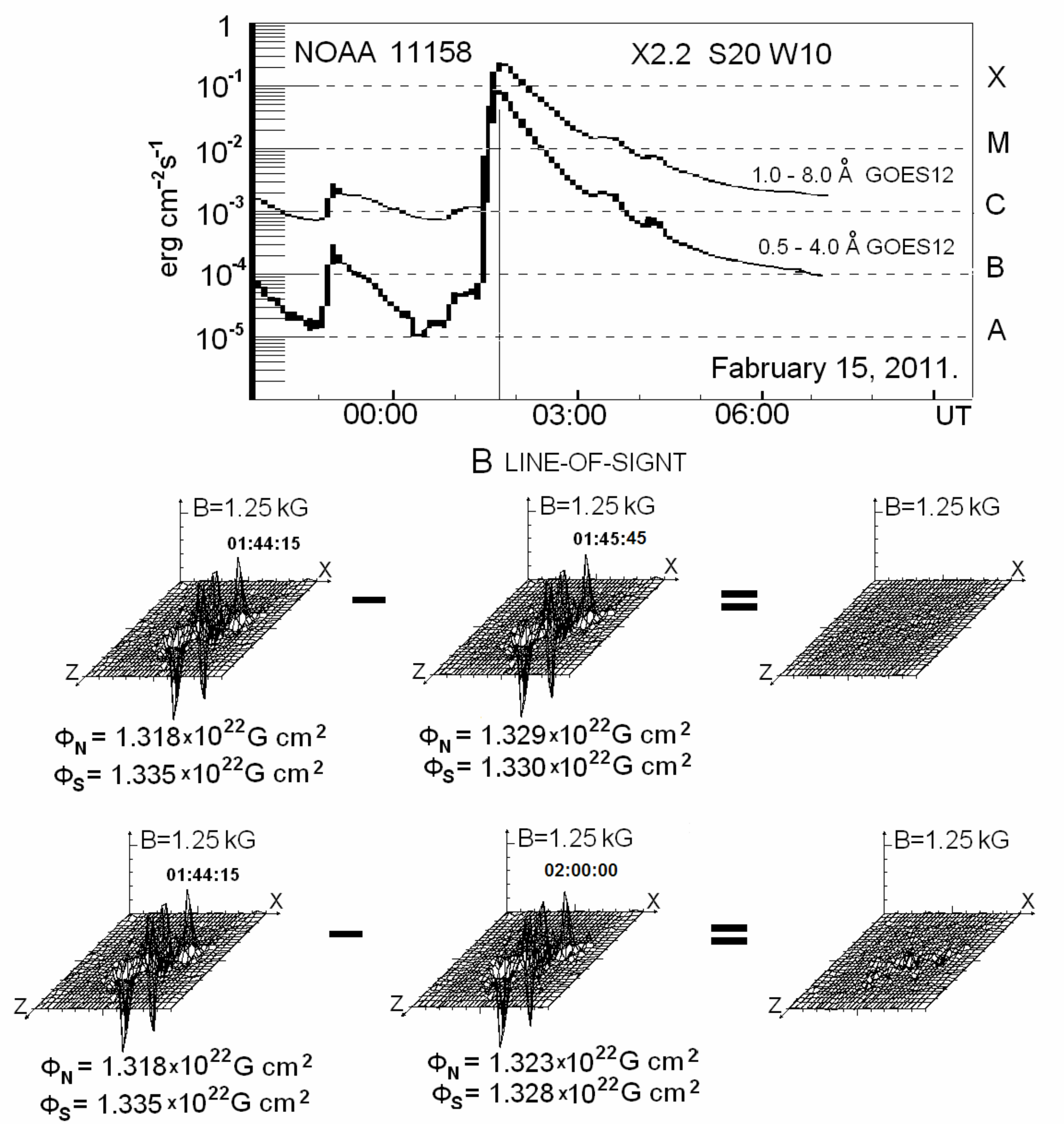

Figure 4. Above - X-rays of the X2.2 flare according to GOES. Below - the distributions of the measured (line-of-sight) component of the magnetic field in NOAA 11158 at the flare and the difference between them. The distributions obtained with 90 s and 16 min intervals. Magnetic field distribution remains constant during the flare.

The data presented in Figure 4 completely rule out the possibility of a flare chromospheric mechanism and indicate dissipation of the magnetic field of the coronal current system, which appeared in the corona in the pre-flare time.

Current sheet in corona

The simplest possibility of current sheet creation above an active region appears at emerging of two magnetic fluxes in the high temperature (high conductive) plasma of the corona.The field lines of two emerging magnetic fluxes that appeared in the same plane are shown in Figure 5.

If increase of the magnetic fluxes occurs in the vacuum, the magnetic vectors addition takes place, and a zero X-type magnetic field line is formed (Figure 5a). The X-line is perpendicular to the figure plane. At two magnetic fluxes emerging in the corona, the magnetic field lines are frozen in the high conducting plasma, and therefore the magnetic fluxes with opposite directed magnetic lines cannot merge immediately. In the initial stage of magnetic fluxes floating-up the currents are generated in the moving boundary between the expending magnetic flux and the unperturbed plasma (Figure 5b). These currents are shown by circles. Magnetic fluxes expanding take place. After some time the boundaries of two independent fluxes meet each other. The independent magnetic fluxes are separated by a current sheet (Figure 5c). During this current sheet formation in the local place of the corona, the magnetic field lines are compressed only around the current sheet in local area of the corona. The reverse current is also localized in the corona. So, the electric current is completely closed in the corona. No new magnetic lines appear in the active region due current sheet creation at the high latitude. The plasma pressure in the current sheet is balanced by the magnetic pressure on both of its sides. The decay of such a current sheet is accompanied by dissipation of energy stored in the current sheet magnetic field. The solar flare appears. The current sheet decay should not cause disturbance of the magnetic field on the photosphere.

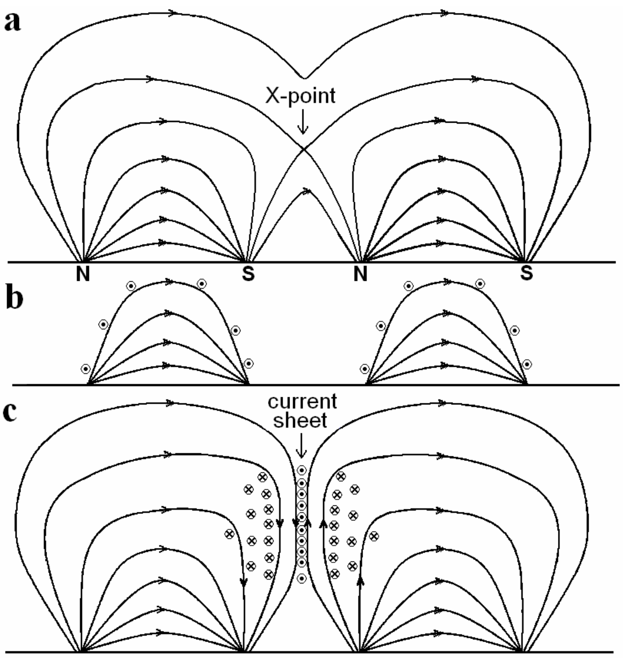

Figure 5.
a). Magnetic field lines of two magnetic fluxes in vacuum.
b). Flowing-up magnetic fluxes in high conductive plasma.
c). Magnetic fluxes interaction creates a current sheet in the corona. Current directions are shown by circles.

Conclusions

The analysis of magnetic field measurements with SOHO and SDO spacecrafts shows:

1. A necessary condition for appearing of a large flare is increase of the active region magnetic flux up to ~10^{22} Mx.
2. Large flares occur in the corona over active regions with complex (βγδ) magnetic field distribution.
3. A bipolar active region cannot produce a flare. The magnetic field in the corona above a bipolar active region does not contain a singular line in the vicinity of which a current sheet can be formed.
4. No change of the magnetic flux and magnetic field distribution in the active region are generated at solar flare appearance.

These conclusions are in agreements with results of 3D MHD numerical simulations that demonstrate current sheet creation in the corona before a flare (Podgorny and Podgorny, 2012a ; 2012b). The magnetic energy accumulated in such a current sheet corresponds to the energy of the flare. It should be emphasized that the current sheet is the only known object in the space that is able to accumulate magnetic energy and then to release this energy explosively. The current sheet in the geomagnetic tail is causing geomagnetic storms. The role of the current sheet in the Earth's magnetosphere became known only after the flight of spacecrafts in the geomagnetic tail. Up to now we have no possibility of magnetic field measurements in the solar corona. The only possibility to get information about magnetic field distribution above an active region is MHD numerical simulation using the measured photosphere magnetic field for setting the initial and boundary conditions.

Acknowledgments

This work was supported by RFBR grant № 13-02-00064, by 22 Program of RAS Prezidium, and by Ministry of Education and Science of RF (contracts 16.518.11.7065 and 02.740.11.0576).

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