

MAGNETIC FIELD DYNAMICS OF LARGE ACTIVE REGIONS IN THE PRE-FLARE STATE DURING SOLAR FLARES

I.M. Podgorny¹, A.I. Podgorny²

¹*Institute for Astronomy RAS, Moscow, Russia, podgorny@inasan.ru*

²*Lebedev Physical Institute RAS, Moscow, Russia*

Abstract. Publications of the active region (AR) behavior before flares and during flares are controversial. In our report in Apatity Seminar 2012 the preliminary data are demonstrated the growth of the magnetic flux of the AR before flares. The X class flares appear, when the magnetic flux of AR becomes bigger than 10^{22} Mx. Apparently the new magnetic flux flowing up from the Sun surface is responsible for energy accumulation in the corona. Another important condition for strong flare appearances is the high magnetic distribution complexity – $\beta\gamma\delta$. The simple β – type AR does not produce a flare. During a solar flare, when the accumulated energy is fast released, there are no any specific magnetic flux changes in AR. This surprising fact follows from the analysis of the array data obtained in recent years for big flares with the SOHO and SDO spacecrafts. It is shown the conservation of the magnetic field distribution in AR during the majority of flares. Small magnetic field changes in the distribution of the field sometimes appear that are typical for the time interval at the flare absence. These results are consistent with the flare theory based on the slow accumulation of the magnetic energy in a current sheet and its explosive realize due to current sheet instability.

Introduction

Long-term observations show that solar flares occur at the AR area, but only the X-ray measurements on spacecrafts Yohkoh and RHESSI [1, 2] have revealed that the primary flare energy release takes place not on the surface of the Sun, but in the corona above AR at the altitude about 20 000 km. The possibility of energy accumulation for the flare in the coronal current sheet has been previously shown in numerical 3D MHD experiments [3, 4]. It has been found that the current sheet is formed in the corona before the flare, and magnetic energy that accumulated in such current sheet is sufficient to produce a flare and coronal mass ejection. This energy is released due to current sheet transition in an unstable state and sheet decay [5]. At the numerical solution of the full system of three-dimensional MHD equations all dissipative terms are taken into account. The initial and boundary conditions on the photosphere are set using the magnetic maps obtained by SDO and SOHO space crafts measurements [6, 7]. No assumptions about the mechanism of the flare are introduced. The current sheet creation occurs because of magnetic field frozen in the plasma of the solar corona.

Disturbances propagating from photosphere in the highly conducting plasma create currents in the corona. These currents are concentrated in the vicinity of a singular magnetic line above AR. Dissipation of currents in the corona during the flare should not change the magnetic flux of the active region. Therefore, the flare may not have an impact on the of the magnetic evolution field of the active region. Due to short duration of the flare (~ 10 min) compared to the duration of magnetic field evolution before the flare (about 5 days), the probability of disturbance appearing during the flare is low. So, the field perturbation of AR during the flare can be only random, as in the case of the field evolution before and after a flare. Magnetic field distribution in AR should not be changed during the appearance of most of the observed flares. In this paper we present new data showing that big (class X) flares occur, when the magnetic fluxes exceed 10^{22} Max, and the magnetic field distribution is very complex. At high magnetic field complexity the conditions for singular lines appear and a possibility arises for current sheet creation in the singular line vicinity [2, 3].

Attempts to detect disturbances of the magnetic field responsible for a flare are carried out many times, but the strong photospheric disturbances during the flare, which could explain the energy released during an flare with the energy of $\sim 10^{32}$ erg, are not detected [8 - 11]. A number of studies examined the possibility of the energy input in the corona during the flare by helicity injection [12]. However, the correlation between the occurrence of helicity injection and flare occurrence is not detected [13].

Analysis of the magnetic field dynamics in AR before the X-class flares have shown an increase of the AR magnetic flux for several days before the flare with the energy above 10^{22} Mx [14 - 18]. In this paper we present new data showing that big (X-class) flares occur when magnetic flux of AR becomes greater than 10^{22} Mx and this AR has a complex field distribution (type $\beta\gamma\delta$). β means existence of the magnetic inversion line in AR, 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 numerical MHD simulation demonstrate that a current sheet can be formed only at the complex field distribution when a singular magnetic line exists in the corona above AR [1, 2] The simple AR, consisting of two sunspots (leading and following), cannot form a singular line in the corona, and therefore and

therefore cannot accumulate energy for a flare. Another important feature of AR is the constancy of the field magnetic distribution during the most of flares, which eliminates the possibility of all the mechanisms of the primary flare energy release on the chromosphere. The flare occurs in the corona above AR. Flares should not cause disturbances of the magnetic field frozen into the dense matter of the photosphere.

It should be emphasized that a current sheet is the only known object in the space that is able to accumulate magnetic energy and then to release it 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 AR is MHD numerical simulation using photosphere magnetic field as boundary conditions.

Active region 10656

The work [19] has concludes that a big flare occurs after increasing the magnetic flux of AR up to 10^{23} Mx. In [14 - 18] it is shown that magnetic flux of AR greater than 10^{22} Mx is the necessary condition for X-class flares appearance. The typical rise time of the magnetic flux is a few days. This condition is necessary but not sufficient. Flares occur only above AR of with the complex field distribution. Bipolar AR with one leading and one following spots, separated by field inversion line of simple form (β -type), does not produce a flare. The typical bipolar region (β -type), and the typical $\beta\gamma\delta$ region with a line inversion of complex shape (γ) and embedded sources of one magnetic polarity in the magnetic field of another polarity (δ), which caused a flare of X-class, are shown in Fig. 1.

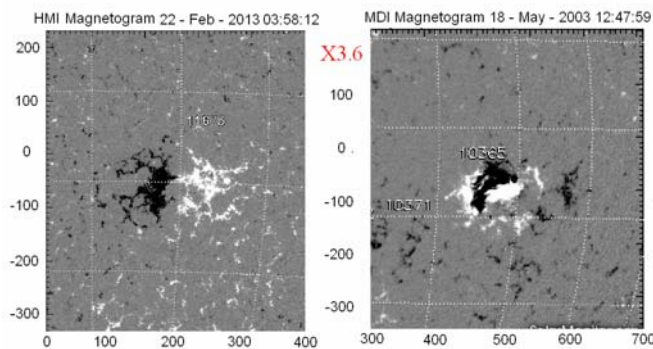


Fig. 1 NOAA 11673 magnetogram with bipolar field distribution (β), which produces no flares, and NOAA 10365 magnetogram with a complex field distribution ($\beta\gamma\delta$), causing the X3.6 flare.

Fig. 2 shows the X-ray emission according to GOES and NOAA 10656 region magnetogramms from 7 to 17 August 2004. NOAA 10656 is formed on the back side of the Sun. It appeared on the eastern limb on the August 7, 2004 with the north and south magnetic fluxes greater than 10^{22} Mx. NOAA 10656 demonstrates the absence of big flares (class X) over several days passage across the solar disk with the magnetic flux of up to 4×10^{22} Mx. Until 11.08.2004 the magnetic field distribution of NOAA 10656 shows two compact groups of field sources of north and south polarity. The magnetic sources of the same polarity are clearly separated by a single inversion line from sources other polarity - the typical type β distribution is demonstrated. Such a bipolar distribution of field sources in the AR forms magnetic loops in the corona. A singular magnetic field line cannot be formed above AR. North and south magnetic fluxes smoothly increase during AR moving across the disk. But photos of magnetogramms shown in Fig. 2 are the results of SOHO MDI measurements of the magnetic field component directed along the line-of-sight, and therefore provide only qualitative estimation of the magnetic flux dynamics. The magnetic field measured by SOHO MDI depends not only on its true value, but also on the angle between the line-of-sight and the Sun surface. To eliminate this effect the magnetic flux is calculated using the field component normal to the solar surface [14]. The normal component is determined by solution of the Laplace equation with boundary conditions in the form of the oblique magnetic potential derivative taken from SOHO MDI measurement [7]. This approximation is valid, if the currents that are responsible for the energy storage for the flare are located high in the corona, as it should be in the case of the flare model based on current sheet creation above AR. Such approach eliminates the dependence of the measured magnetic components on the position of the AR on the Sun. The magnetic flux – time dependence in Fig. 2 is obtained by calculating the normal component of the magnetic field [4].

The magnetic flux of NOAA 10656 increases during a week from 10^{22} Mx to $\sim 4 \times 10^{22}$ Mx. Despite the great importance for northern and southern magnetic fluxes for flare appearance, AR NOAA 10656 does not produce any big flares until August 13. All this time AR NOAA 10656 magnetic configuration does not reveal high magnetic field complexity. Later, the field configuration of AR becomes a more complex. By this time the configuration of the field has changed: the sources of the one polarity are embedded in the field of other polarity, and the field inversion line has a rather complicated form. Field distribution becomes $\beta\gamma\delta$ type. Magnetic flux in AR reaches $(3-4) \times 10^{22}$ Mx, and the field distribution complexity is also gradually increased. Correlation of flare activity with the increasing complexity of the field distribution in the area is clearly seen. Along with the magnetic flux increasing and the complexity of the field distribution in NOAA 10656 the flare activity also increases. X1 flare appears on

August 13, and then a series of flares of class M appear. Until August 13, the class of solar flares produced by the region NOAA 10656, is not exceeded the class C. The flare of class X1 appears only on August 13 at magnetic flux $\sim 4 \times 10^{22}$ Mx. This big flare is accompanied by a series of flares of class M occurred on August 14 and 15. From comparison of magnetic flux time dependence and the magnetograms shown in Fig. 2 one can conclude that flare activity takes place not only due to slow increasing of AR magnetic flux, but also because of the complicity of magnetic field distribution.

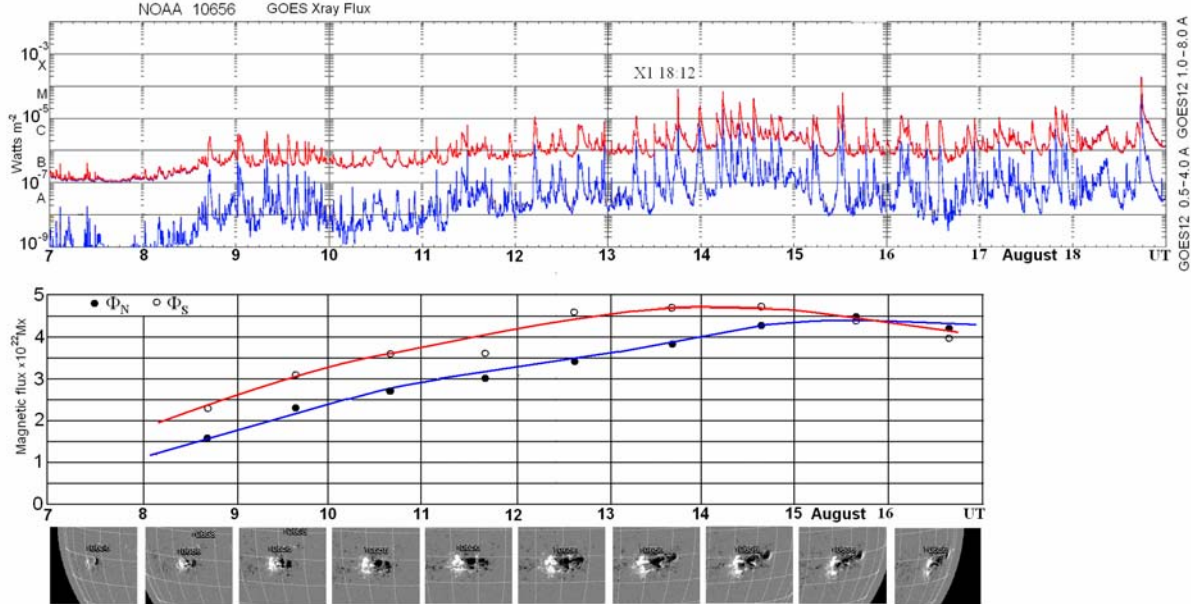


Fig. 2 X-ray dynamic produced by AR NOAA 10656 and magnetograms

In contrast to AR NOAA 10656, which have a big magnetic flux for 5 days, but not complicated distribution of the magnetic field, AR NOAA 10365, 10720, 11158, discussed in [13-17], have a complex distribution of the magnetic fields of the type $\beta\gamma\delta$ and caused a series of very big flares at lower magnetic flux.

All the time of NOAA 10656 traveling on the visible disk, AR field distribution is not as complex as the field of NOAA 10365, 10720, 11158 that produced many flares. AR NOAA 10656 have produced only one flare of class X (X1) after distribution complicity increasing. The data presented here suggest two factors that determine the onset of pre-flare situation for big flares: the increase of the magnetic flux above the critical value of $\sim 10^{22}$ Mx and the complexity of the distribution of the magnetic sources on the photosphere, in particular the complexity of the shape of the field inversion line.

The constancy of active region magnetic field distribution during a flare

It has been shown in [14-20] that the magnetic flux of AR remains unchangeable even during large flares. This conclusion seems contradicts the fact that the source of the flare energy is the Sun. However, by visual analysis of photographs of the magnetograms and magnetic field distributions in the active regions during the flares any even slight changes that could be associated with flare appearance has not found. Only at the giant flare X17 28 October 2003 in NOAA 10486 a narrow maximum of ~ 1000 G has been registered, which is not cause a noticeable change in the magnetic flux of the active region. The magnetic flux during this flare also has remained constant to within 1%.

Comparison of the magnetic field distributions measured on February 15, 2011 near the flare X2.2 maximum has been carried out in details in the present work. The time interval between measurements is 90 s. The half-width of X-ray flare pulse does not exceed ~ 20 min. Fig. 3 shows the distribution of the magnetic fields at two time moments around the flare maximum (1:44:15 and 1:45:45) and the difference of these distributions. It is clearly seen the preservation of magnetic field distribution at the flare maximum. The north and south magnetic fluxes of AR remain constant to within 1%. During this flare the AR position is S21 W21. The angle between the line-of-sight at the measurement and the normal to the Sun surface is about 30° . Highly constancy of the distribution of the line-of-sight component shows that at the maximum energy release of the X2.2 flare on February 15, 2011 not only the normal magnetic field component is preserved, but the tangential component remains also constant. This means that the energy of the magnetic field, which quickly released during the flare, has been transported to the corona in the pre-flare state and accumulated in the current system (current sheet) above the active region.

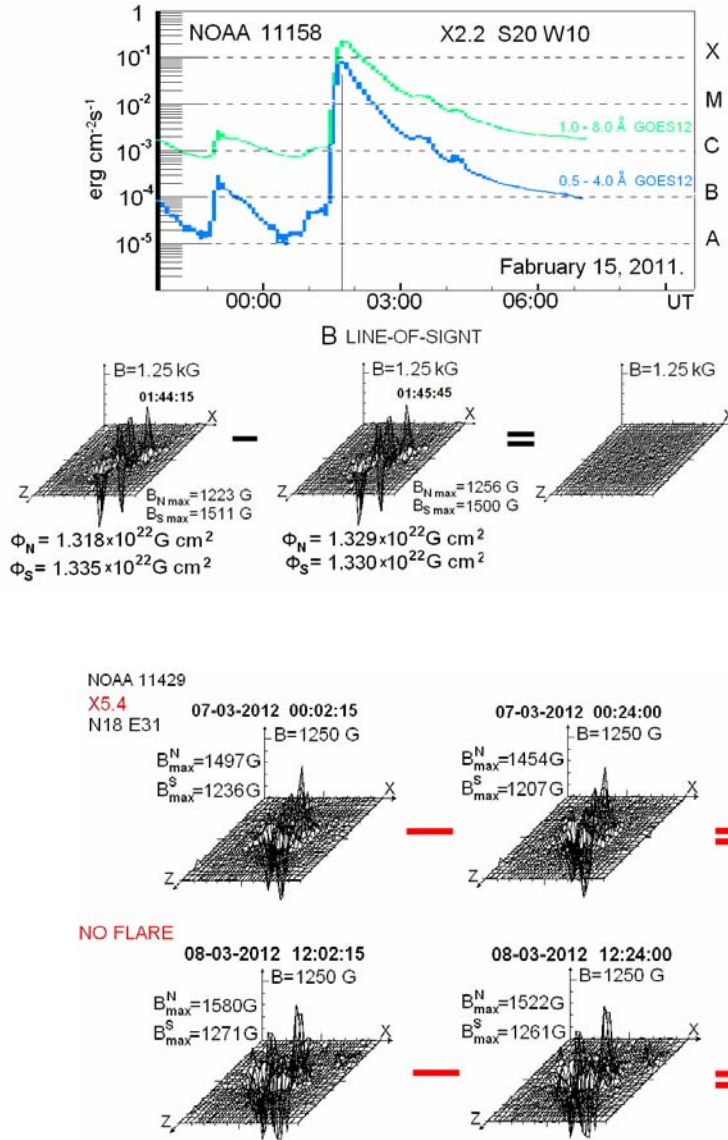


Fig. 3 Above - X-rays of the X2.2 flare according to SDO. Below - the distributions of the measured (sight-of-line) component of the magnetic field at the flare maximum obtained with 90 c interval and the difference between them. Magnetic field distribution remains constant during the flare.

Fig. 4 The distributions of the measured line-of-sight component of the magnetic field obtained during the X5.4 flare and during quiet time 36 h after this flare. The distributions are obtained with 22 min interval, and the differences between them are shown.

Another example of conservation of magnetic field distribution and the magnetic flux of the active region is shown in Fig. 4. The X5.4 flare is occurred in AR NOAA 11429. This flare duration exceeds 30 min. The distributions of the magnetic field taken at intervals of 22 minutes during the flare and during the quiet state of the Sun 36 hours after the flare is appeared. No characteristic features are seen in the dynamics of the magnetic field distribution in AR and the magnetic flux during the flare. In both cases, the distribution of the field and the magnetic flux on the solar surface are conserved up to three decimal places.

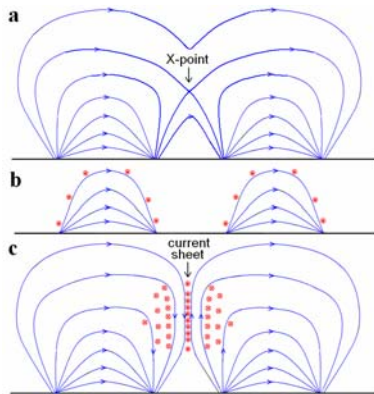


Fig. 5 a). Magnetic field lines of two fluxes in vacuum. b). Flowing-up magnetic fluxes in high conductive plasma. c). The magnetic fluxes interaction creates a current sheet in the corona. Current directions are shown by circles.

The data presented in Fig. 3 and Fig. 4 completely rule out the possibility of flare chromospheric mechanism and indicate dissipation of the magnetic field of the coronal current system, which appeared in the pre-flare state.

Current sheet in corona

The simplest possibility of current sheet creation above AR appears during emerging of two magnetic fluxes in the highly conductive plasma of the corona. The diagrams of two emerging magnetic fluxes that appeared in the same plane are shown in Fig. 5.

If increase of the magnetic fluxes occurs in the vacuum, the magnetic vector addition takes place, and a zero X-type magnetic field line perpendicular to the figure plane is formed. In highly conducting plasma the magnetic field lines are frozen into the plasma, and therefore the magnetic fluxes with opposite directed magnetic lines cannot merge immediately. The plasma motion with frozen-in magnetic lines builds a current sheet that separates two different magnetic fluxes. In the initial stage of magnetic fluxes floating-up the currents are generated in the moving boundary between magnetic flux and the unperturbed plasma. 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. During a local current sheet formation, the distortion of the magnetic field takes place only in a local area of the corona. Reverse current is also localized in the corona. So, the current is completely closed in the corona. No new magnetic lines appear in the active region due current sheet creation. The new magnetic field lines are closed inside the corona. 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.

Conclusion

1. The necessary condition for appearing of a big flare is an increase of AR magnetic flux up to 10^{22} Mx.
2. Big flares occur in the corona over active regions with complex ($\beta\gamma\delta$) magnetic field distribution.
3. The bipolar region cannot produce a flare. The magnetic field in the corona above the bipolar AR 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 AR are generated due to solar flare appearance.

Acknowledgments. This work was supported by RFBR grant № 13-02-00064 and by 22 Program of RAS Prezidium.

References

1. Lin R. P., Krucker S., Hurford, G. J. *et al.* *Astrophys. J.* **595**, L69, 2003.
2. Masuda S., Kosugi T., Hara H., Tsuneta S., Ogawara Y. *Nature*. **371**. №6497, 495, 1994.
3. Podgorny A. I. and Podgorny I. M. *Geomagn. and Aeronomy*. **52**, 150, 2012.
4. Podgorny A. I. and Podgorny I. M. *Geomagn. and Aeronomy*. **52**, 162, 2012.
5. Podgorny A. I. *Solar Phys.* **123**, 285, 1989.
6. <http://soi.stanford.edu/magnetic/index5.html>
7. <http://jsoc.stanford.edu/ajax/lookdata.html>
8. Falconer D. A., Moor R. L., and Gary G. A. *Astrophys. J.* **644**, 1258, 2006.
9. Leka K. D. and Bames G. *Astrophys. J.* **656**, 1173, 2007.
10. Petrie G. J. D., Sudol J. J. *Astrophys. J.* **724**, 1218, 2010.
11. Wang J., Zhao M., Zhou G. Magnetic changes in the course of the X7.1 solar flare on 2005 January 20. *Astrophys. J. V.* **690**, 862, 2009.
12. Jiang Y., Zheng R., Yang J. *et al.* *Astrophys. J.*, **744**. P. 500-505, 2012.
13. Kusano K. *Adv. Space Res.* **32**, 1917, 2003.
14. Podgorny A. I. and Podgorny I. M. *Astronomy Reports*. **55**, 629, 2011.
15. Podgorny I. M., and Podgorny A. I. *Phys. Auroral Phen. Proc.* **33** Annual Seminar. Apatity, 2010. P. 87.
16. Podgorny I. M., and Podgorny A. I. *Phys. Auroral Phen. Proc.* **35** Annual Seminar. Apatity, 2012. P. 88.
17. Podgorny I. M. and Podgorny A. I. *Journal of Atmospheric and Solar-Terrestrial Physics. Journal of Atmospheric and Solar-Terrestrial Physics* **92**, 59, 2013.
18. Podgorny I. M. and Podgorny A. I. *Astronomicheskii Tsirkular*. №1586. January 24, 2013.
19. Ishkov V. N. *Astronomical and Astrophysical Trans.* **20**, 563, 2001.
20. Podgorny I. M., Podgorny A. I. *Pulkovo*. 2010. P. 315.