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First flare M 1.9 AR 10365: comparing results real-scale time MHD modeling and observational data

BorisenkoA.V.[1], PodgornyI.M.[2], PodgornyA.I.[1]

[1]Lebedev Physical Institute of the RAS, Moscow, Russia
[2]Institute of Astronomy of the RAS, Moscow, Russia
E-mail: sunw77@mail.ru

Abstract

As shown the first results of MHD modeling in real scale of time above the active region (AR) 10365, the maximum current density appeared before the first flare M 1.9 (05/26/2003 05:34) in the neighborhood of an X-type singular line of magnetic field with superimposed diverging magnetic flux at heights of about 18,000 km (in lower corona). Ground based (NobeyamaNoRH 17 Ghzradioheliographic data) and space (SOHO) data also confirm finding of flare source M 1.9 (GOES class) at heights of solar corona. Since the configuration (singular X-type line) – supposed flare source is clearly visible in coronal ultraviolet lines of iron Fe IX / X, Fe XII, Fe XV (SOHO / EIT 171A, 195A, 284A), authors suggest possible formation of current sheets at heights from lower corona up to heights more above 18000 km (radioheliographic data NoRH 17 Ghz). The first results of MHD modeling in real scale of time showed high precision with compare observed data (in particular to form X-type magnetic configuration of first preflare source over multi flare AR 10365).

Introduction

As know, solar flares are the most powerful phenomena of solar activity. Flares always occur above active regions, where local magnetic fields of several thousand Gauss are much stronger than the surrounding these active regions of solar mean magnetic field (about of several Gauss). This permit to conclude that the energy released at the flare should first be accumulate in the magnetic field. It is very possible that nature of small scale micro and nano flares are similar, because it is difficult to propose for them another mechanism of slow accumulation and then fast release of magnetic energy. The forecast of solar flares and the appearance of solar cosmic rays (SCR) and other solar flare manifestations is an important scientific and technical task. This idea of the accumulation of solar-flare energy in the magnetic field of a current sheet was suggested by the famous Soviet physicist and astrophysicist Sergei Ivanovich Syrovatskii (1925–1979) (Syrovatskii, 1966). The flare model, the main model based on the current sheet, have some features of the pinch-based flare model proposed early other famous researchers. In fact, a current sheet is an analog of a pinch, which can be produced in the solar corona plasmaas a result of the accumulation of small perturbations that propagate from the solar surface. Therefore, S.I. Syrovatskii introduced the term "pinch current sheet". There are also other theories that describe flare scenarios with the use of models of force-free magnetic fields. However, it is not completely clear, for example, how very small perturbations of the photospheric magnetic field, which occur before flares, canlead to the accumulation of magnetic energy in twisted magnetic-line tubes (ropes) high above the photosphere. The magnetic tubes obtained in the force-free approximation are unstable and rapidly disintegrate. Difficult to imagine how energy can accumulate long time in such magnetic structures for a flare. In 1988, Igor Maksimovich Podgorny (1925–2018) suggested an electrodynamic model of a solar flare (Fig. 1) [*Podgorny and Podgorny*, 2012]. Based on that model, the evolution of the current sheet was numerically simulated for the first time [*PodgornyandPodgorny*, 2003]. The numerical solution of a set of three-dimensional magnetohydrodynamic (MHD) equations with dissipative terms for compressible plasma with anisotropic thermal conductivity was implemented in the Fortran program PERESVET.This program realized absolutely implicit finite-difference schemeconservative relative to magnetic flux, which was specially developed to accelerate calculations [*Podgorny and Podgorny*, 2004, 2018].

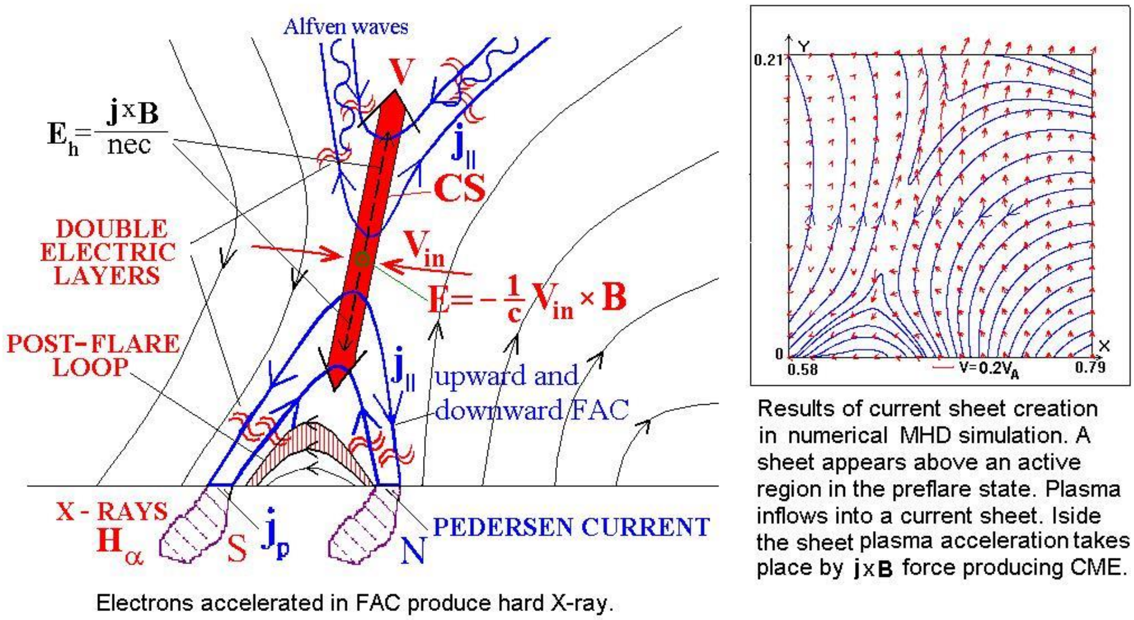

Fig. 1. Electrodynamic model of a solar flare by I.M. Podgorny based on Interkosmos-Bulgaria-1300 satellite measurements.

The current sheet is formed in the neighborhood of an X-type singular line of the magnetic field, due to field deformation by plasma flow caused by **j**×**B** force. Due to essential resistivity of thin current sheet, the freezing-in condition in it is violated, and in the geometry of X-type configuration it appears impression, that magnetic lines moves to the sheet, reconnected in the sheet, and then moves from the sheet with plasma outflow. Therefore, the process in the sheet as called as "magnetic reconnection". During quasi-stationary evolution of the sheet the plasma density drops with time in the sheet and near it due to fast outflow from the sheet under the action of strong magnetic tension (**j**×**B**) force. When due to such strong outflow the plasma density near the sheet becomes less than the threshold value and so the plasma near the sheet cannot stabilize the instability. During the instability the balance between the plasma pressure plasma in the sheet and magnetic pressure is violated so the current sheet shrink fast under the action of plasma pressure. Therefor fast magnetic dissipation occurs with flare energy release [*Podgorny 1989; Podgorny and Podgorny, 2012*].

To obtain the correct development of physical processes in time, it is necessary to carry out MHD simulation in the real scale time. MHDsimulationin corona above the AR allows us to find the appearance of current sheets in the solar atmosphere which are sources of magnetic energy of flares.In view of the appearance of solar flares high in the corona, as well as the impossibility of obtaining from observations the configuration of the magnetic field in the corona, in order to study the mechanism of flares and their prognosis, MHD simulation in the corona above the AR is necessary [*Podgorny and Podgorny, 2012*].In the conditions of complicated configuration of magnetic field in the solar corona the appeared current sheets can be found using specially developed graphical system of search basing of the founding of local current density maxima [*Podgorny et al., 2013, 2017; 2018*].In spite of using specially developed methods, calculations are performed rather slow, and MHD simulation above the real active region using ordinary computer is possible only in strongly reduced (in 10^4 times) time scale [*Podgorny and Podgorny, 2013, 2017, 2018*]. MHD simulation in real scale of time become possible using parallel computing on Nvidia GPUs using CUDA technology [*Borisenko e tal*., 2020]. Modernizing of algorithm with using possibilities of modern hardware and software permit accelerate of computations more few hundred speed up times.MHD simulation in strongly reduced time scale showed the appearance of numerical instability near thephotospheric boundary due to unnaturally fast magnetic field increase on the photosphere [*Podgorny et al., 2013, 2017*].For MHD simulations in the real scale of time, numerical instabilities unexpectedly appear at the photospheric and non-photospheric boundaries of the computational domain, which have time to develop over a long calculation interval. These instabilities were stabilized thanks to specially developed methods [*Podgorny et al., 2021*].

In the general case, a magnetic field near the X-type singular line can be superimposed on a "mirror cell" -type field, diverging along the singular line (see [Podgorny et al., 2021] for details). If the X-type field dominates the diverging field, the result is a deformed X-type field, in which the magnetic lines are hyperbolic. In this case, each magnetic line lies in one of four sectors, into which two intersecting planes divide the space. If a diverging magnetic field dominates, then the magnetic lines are parabolic and the space does not share sectors with magnetic lines. But, as shown by MHD simulation, even in this case, a sufficiently powerful current sheet can also appear in the vicinity of the singular line, since the X-type magnetic field is also present in the superposition of fields.

Active Region 10365: observational data and results MHD modelling

AR 10365was interesting because from May 26 - June 3, 2003, was produced 49 flares were observed (C M and X GOES class). After several flares was produced coronal emission mass (CME), as well as the acceleration of SCR, which were dangerous for people and equipment in the near-Earth space, Earth polar latitudes.

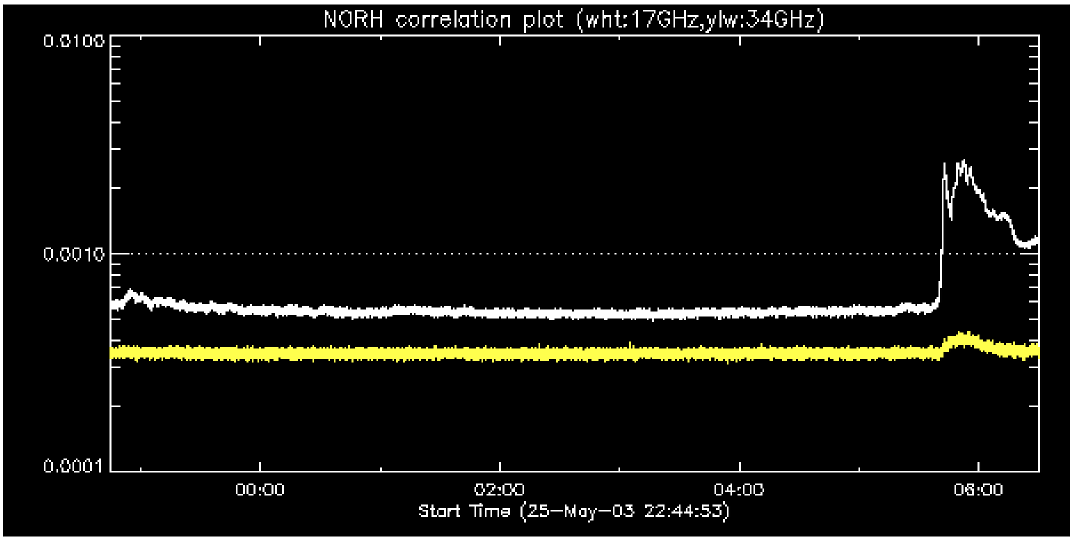

Fig. 2. NoRH 17 ghz plot (25-26 May2003) (from NobeyamaRadioHeliograph Team)

First flare M 1.9 (05/26/2003 05:34) was detected different ground-based and space instruments. For example on Fig. 2 shows a white curve (NoRH 17 GHz) at 05: 34 at the nearest time, a sharp signal amplification is observed, until this moment a quit background was observed.

In Fig. 3 shows the projections of magnetic lines on the central plane perpendicular to the photosphere and parallel to the solar equator, magnetic lines in three-dimensional space and their projections onto the picture plane (perpendicular to the line of sight). The positions of the current density maxima are indicated by green dots. In the vicinity of point 1 (the 115th

maximum of the current density, all the maxima are numbered in decreasing order), an X-type field configuration appeared (Fig. 4). In the vicinity of point 2 (the 5th maximum of the current density, which is the maximal near the position of the flare) a divergent field is superimposed on the X-type configuration (Fig. 5).

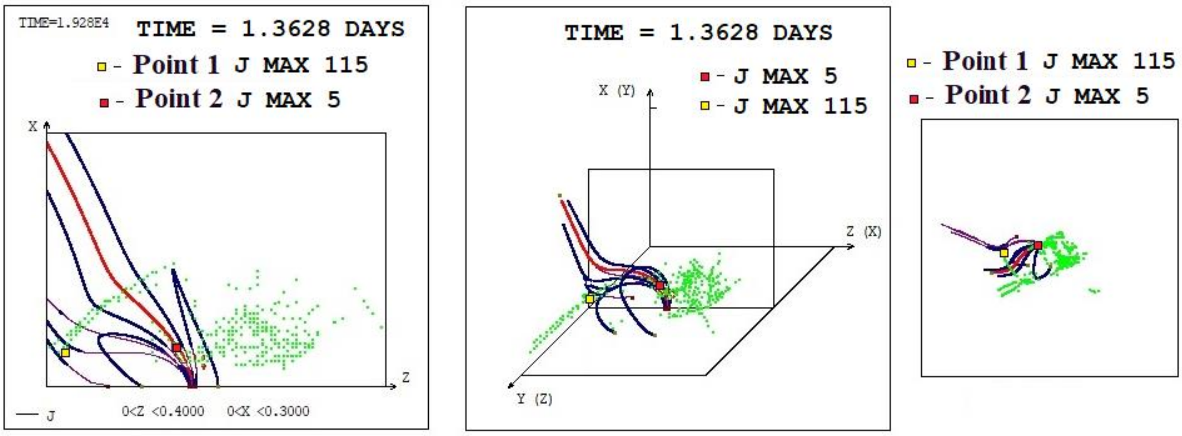

Fig. 3. The magnetic field configuration and the maximums of the current density in the computational domain at the time of the first flare of M 1.9 in AR 10365(1.3628 days after beginning of simulation).

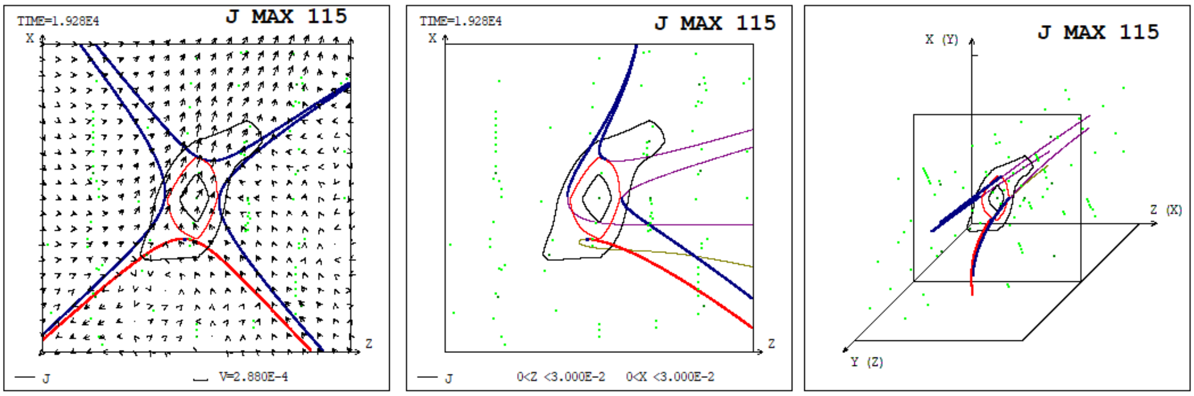

Fig. 4. Plane magnetic lines (tangent to the projections of the magnetic field vectors on the plane of the configuration of the current sheet) with the velocity vectors, the projections of the magnetic lines on the plane of the configuration (which is perpendicular to the magnetic field vector at the point of maximum current density, in which the current sheet is most distinctly pronounced) and three-dimensional magnetic lines in the vicinity of point 1 (115th maximum of the current density).

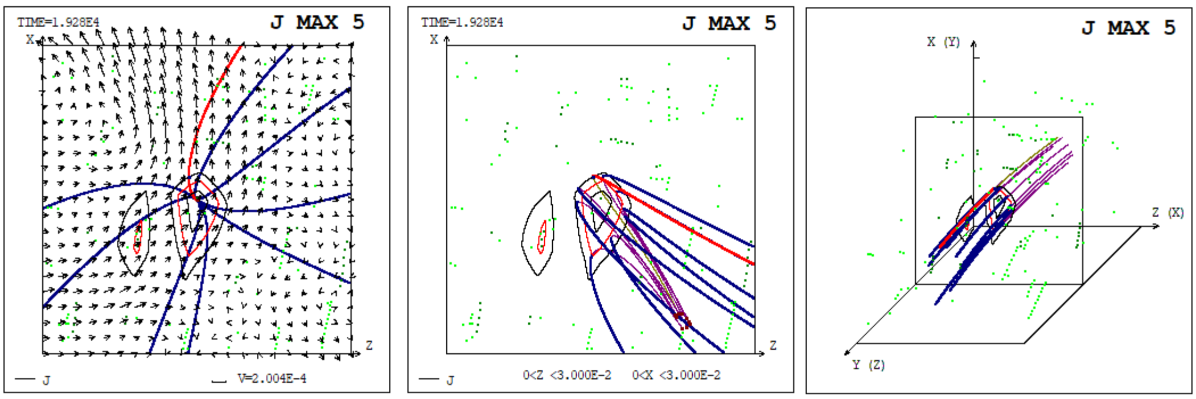

Fig. 5. Magnetic field configuration in the vicinity of point 2 (5thmaximumof current density).

On Fig. 6 show the AR 10365 for greater clarity at the same zoom scale (approximately 0.6" sec/pixel) for different instruments (SOHO/MDI images, SOHO/EIT 171A, Nobeyama radioheliograph NoRH 17 Ghz) at close moments (more precisely, moments 4.5 hours before the start of the first flare M 1.9 26.05.2003 05: 34). Additionally, Po and Bo angles were corrected to more precision overlaid the Nobeyama radioheliograph ground-based data and SOHO data. On Fig. 6a showed superimposed bright loop from the NoRH 17 Ghz image coincides with points 1 and 2 with high precision. Bright emission areas on NoRH 17 Ghz wave show presence of strong magnetic fields. The green points showed are the current density maximums.

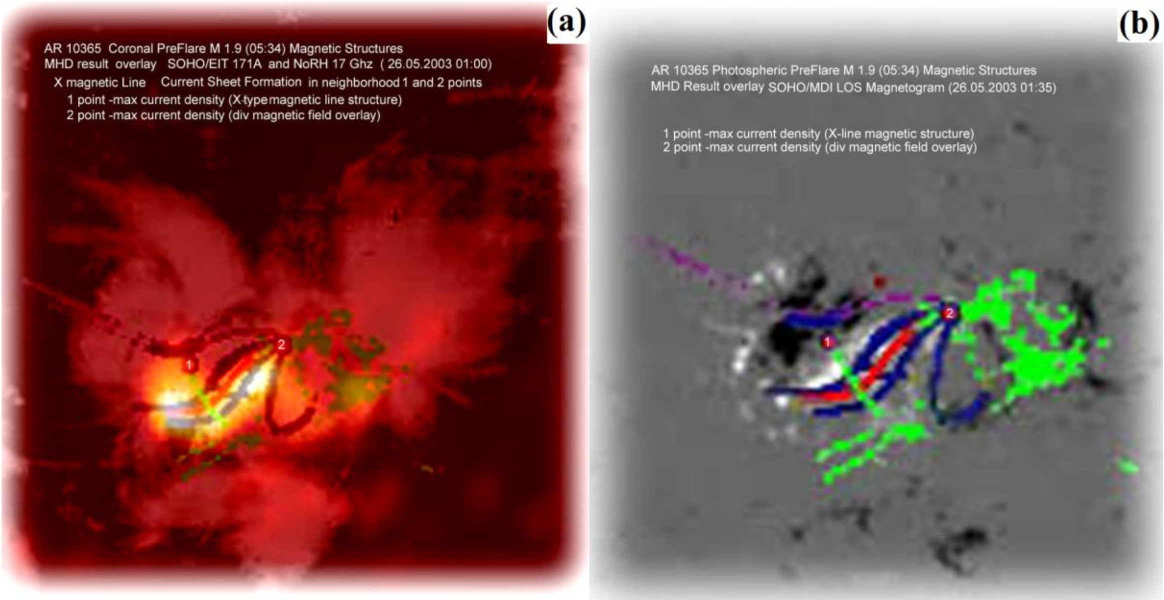

Fig. 6. AR 10365 coronal magnetic structures (a) and AR 10365 photospheric magnetic structures (b) before flare M 1.9 (26.05.2003 05:34) with superimposed MHD simulation results.

Point 1 above the left negative magnetic field region (Fig. 6b, SOHO/MDI Magnetogram black areas), point 2 is located above the right in the positive magnetic field region (SOHO/MDI Magnetogram white areas). After 4.5 hours, at the place under the top of the loop, Nobeyama will show a bright flare emission (starting of the first flare M 1.9 26.05.2003 05:34) exactly at the place where the intersection occursthe current density maximums (green dotted curve line) from point 1 and the open divergent magnetic flux from point 2.

Conclusion

From results of MHD modeling received the height of the current sheet formation in the neighborhood of a singular X-type line about 18,000 km. This is 'pre-flare events' clear viewed take place from the lower corona ahd higher (SOHO/EIT 171A Fe IX/X ionisation temperature ~ 800 000 -1,300,000 K, Nobeyama radioheliograph 17 Ghz).

Thus, similar pre-flare magnetic structures (X-type line or more complex configurations with superimposed divergent magnetic field) in the neighborhood of a current sheet occurs (who may longenergy accumulation 'energy budget' for a flare) are characteristic of many multi-flare AR on the Sun.

Since the image of the MHD results coincides well with the structures from superimposed images of different tools, we can conclude that the high precision of the MHD modeling performed in real scale of time is occur maybe for future flare forecasts.Thus, solar flare mechanism, based on the accumulation of energy in current sheet (in the neighborhood of X-type singular magnetic line), proposed by S.I.Syrovatskii and other known-well researchers was confirmed for first flare AR 10365 the obtained results of MHD modeling inreal scale of time.

Acknowledgments

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