

## Research Article

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# Comparing results of real-scale time MHD modeling with observational data for first flare M 1.9 in AR 10365

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**Abstract:** As shown in the first results of MHD simulations in the real scale of time, above the active region (AR) 10365, during the first flare M 1.9 (05/26/2003 05:34) at a height of 16–18 mm (lower corona), a singular line of magnetic field appears. The local maximum of the current density is situated on this singular line. The magnetic field in the vicinity of this singular line is the superposition of an X-type magnetic configuration and a divergent magnetic field. The accumulation of magnetic energy for solar flare with current sheet creation takes place near this singular line due to magnetic field deformation by disturbances in the X-type configuration in spite of the presence of overlaid diverging magnetic configuration. The magnetic configuration is so complicated that the singular line can be found only by using specially developed graphical system of search. The position of singular line coincides with position of source of flare radio emission at the frequency 17 GHz above AR 10365 measured by Nobeyama Radioheliograph (NoRH). Also, MHD simulation shows appearance of the singular line, in the vicinity of which X-type configuration dominates. However, apparently due to small disturbance, propagating from the photosphere, sufficient magnetic energy was not accumulated in this configuration, so the NoRH does not show the flare source of emission at the frequency 17 GHz in the place, where this singular line is situated.

**Keywords:** Sun, solar flares, magnetic reconnection, current sheet, parallel computing, magnetohydrodynamics

## 1 Introduction

As known, solar flares are the most powerful phenomena of solar activity. Flares always occur above active regions (ARs), where local magnetic fields of several thousand Gauss are much stronger than the surrounding these ARs of solar mean magnetic field (about several Gauss). This permit us to conclude that the energy released at the flare should first be accumulated in the magnetic field. It is possible that nature of small scale micro- and nano-flares is 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) in work (Syrovatskii 1966). The flare model, the main model based on the current sheet, has some features of the pinch-based flare model proposed earlier by other famous researchers. In fact, a current sheet is an analog of a pinch, which can be produced in the solar corona plasma as a result of the accumulation of small perturbations that propagate from the solar surface. Therefore, Syrovatskii introduced the term “pinch current sheet.” In 1988, Igor Maksimovich Podgorny (1925–2018) proposed an electrodynamic model of a solar flare (Figure 1), which explains the main observational manifestations of the flare. According to this model, the hard X-ray beam radiation on the surface of the sun during a flare is explained by the deceleration in the lower dense layers of the solar atmosphere of electron fluxes accelerated in

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this maximum of the current density in comparison with others.

### 3 Simulation in the real scale of time, stabilization of instability at boundaries, and search for flare positions

In spite of using specially developed methods (Podgorny Podgorny 2004), computations are performed rather slow, and MHD modelling above the real AR using ordinary computer is possible only in strongly reduced (in 10,000 times) time scale. Otherwise, the computations will be delayed for any years. Details are presented in Podgorny and Podgorny (2013), Podgorny *et al.* (2017), and Podgorny *et al.* (2018). MHD modelling in real scale of time becomes possible using parallel computing on Nvidia GPUs using CUDA technology (Borisenko *et al.* 2020). Modernizing of algorithm with using possibilities of modern hardware and software permits acceleration of computations more few hundred speed up times. MHD modelling in strongly reduced time scale showed the appearance of numerical instability near the photospheric boundary due to unnaturally fast magnetic field increase in the photosphere (Podgorny and Podgorny 2013, Podgorny *et al.* 2017)

The calculation was carried out at low magnetic and ordinary viscosities, the dimensionless values of which were  $\nu_m = 10^{-9}$  (magnetic Reynolds number  $R_m = 10^9$ ) and  $\nu = 10^{-7}$  (Reynolds number  $R = 10^7$ ). This made it possible to efficiently accumulate magnetic energy for a flare in the corona without suppression by viscosity; however, numerical instabilities arose near the boundary of the region. To stabilize the numerical instabilities, in addition to using specially developed methods, including the introduction of artificial viscosity near the boundary, it was also necessary to decrease the time step by several orders of magnitude (Podgorny *et al.* 2021).

The idea of the accumulation of energy for a flare in the magnetic field of a current sheet above an AR opens up opportunities to find positions of solar flares in corona above the AR using results of MHD simulation.

In the solar corona the magnetic field configuration near the current sheet is so complicated, that in obtained by MHD simulation magnetic field configuration practically it is impossible to find the place where the current

sheet is situated. The appearing current sheets can be found using a specially developed graphical search system (Podgorny and Podgorny 2013, Podgorny *et al.* 2017), which is based on the fact that the absolute value of the current density is maximal in the middle of the current sheet. In the vicinity of the point of maximum current density, which, most likely, should lie on an X-type singular line, the configuration of the magnetic field is investigated. The analysis of the magnetic field configuration is carried out primarily in the so-called configuration plane, i.e., in the plane perpendicular to the magnetic field vector. This vector is taken at the point of maximum current density. In this plane, the configuration of the magnetic field is most pronounced.

MHD simulations have shown that a divergent magnetic field can often be superimposed on a singular X-type line (Podgorny 1989, Podgorny *et al.* 2018, 2021). In this case, the X-type configuration field can dominate, so that a deformed X-type configuration is obtained as a result of the superposition. In other cases, a diverging magnetic field may dominate, so the deformed diverging magnetic field is a result of superposition. However, as calculations show, even in the case of dominance of a diverging field, since the X-type configuration is also present in the superposition of fields, a sufficiently powerful current sheet can be formed under the influence of disturbances. This current sheet can cause a flare of low and even medium power.

Examples of the dominance of the X-type configuration (the 115th maximum of the current density) and the configuration of the diverging field (the 5th maximum of the current density) for the flare M 1.9 05/26/2003 05:34 in AR 10365 are shown in Figures 8 and 9. All current density maxima are numbered by the graphic search system in descending order of current density at the maximum. Configuration of the field resulting from the superposition of the X-type configuration and the diverging magnetic field is described in detail in Podgorny (1989), and Podgorny *et al.* (2018, 2021).

The MHD simulation has shown the formation of a large number of current density maxima. This can be the effect of inaccurate numerical solution on a grid that is too rough for the low magnetic and usual viscosities used. In the future, it will be necessary to try to choose the step of the spatial grid, which will better correspond to the used viscosities. Here, the study of the mechanism of a solar flare is carried out by comparing the position of the groups of current density maxima and the position of the most powerful maximum in the group with the observed position of the flare.

## 4 AR 10365: observational data and results of MHD simulation

AR 10365 passed in center disk of Sun (Figure 2) was interesting because from May 26 to June 3, 2003, 49 flares were observed (C M and X GOES class). After several flares coronal mass emission (CME) was produced, as well as the acceleration of SCR, which was dangerous for cosmonauts and equipment of spacecrafts in the near-Earth space. First flare M 1.9 (05/26/2003 05:34) was detected by Nobeyama Radioheliograph (NoRH)

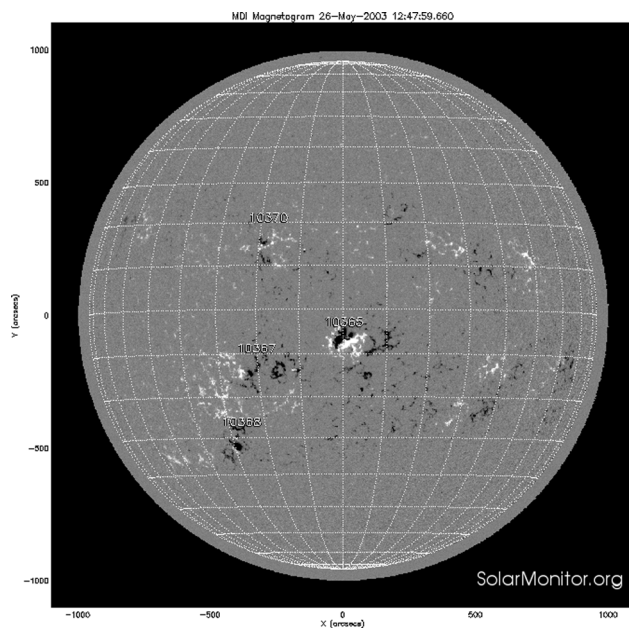


Figure 2: AR 10365 SOHO/MDI Magnetogram 05/26/2003.

17 GHz. Figure 3 shows a white curve of NoRH radioemission observation at a frequency of 17 GHz. At the nearest time to 05/26/2003 05:34 a sharp signal amplification is observed, until this moment a quiet background was observed.

Figures 4–9 show the results of MHD simulations in real time and their superposition on the distribution of the intensity of radio emission at a frequency of 17 GHz, for the study of the first flare above AR 10365.

Figures 4 and 5 represent the situation 4.5 h before the flare, when the accumulation of magnetic energy in the corona should begin; and Figures 6 and 7 present the results during flare. Figures 4 and 6 show the configuration of the magnetic field in three-dimensional space and in the central plane  $z = 0.5$  in the central part of the computational domain  $160 \text{ mm} \times 120 \text{ mm} \times 160 \text{ mm}$  ( $0.4 \times 0.3 \times 0.4$  in dimensionless units) with a large magnetic field. The central plane is located in the middle of the computational domain perpendicular to the photosphere and parallel to the solar equator. Figures 5 and 7 show the superimposition of the MHD simulation results on the intensity distribution of radio emission at a frequency of 17 GHz, obtained with the NoRH. For the convenience of presenting the three-dimensional configuration, in Figures 4 and 5, the magnetic line is highlighted, passing through the middle group of maxima located at an altitude of 50–60 mm, and in Figures 6 and 7 the magnetic line is highlighted, passing near the 5th maximum. The highlighted line is indicated as bold red in front of the central plane and as thin brown behind the central plane. The rest of the lines is indicated as bold blue in front of the central plane and as thin purple behind the central plane.

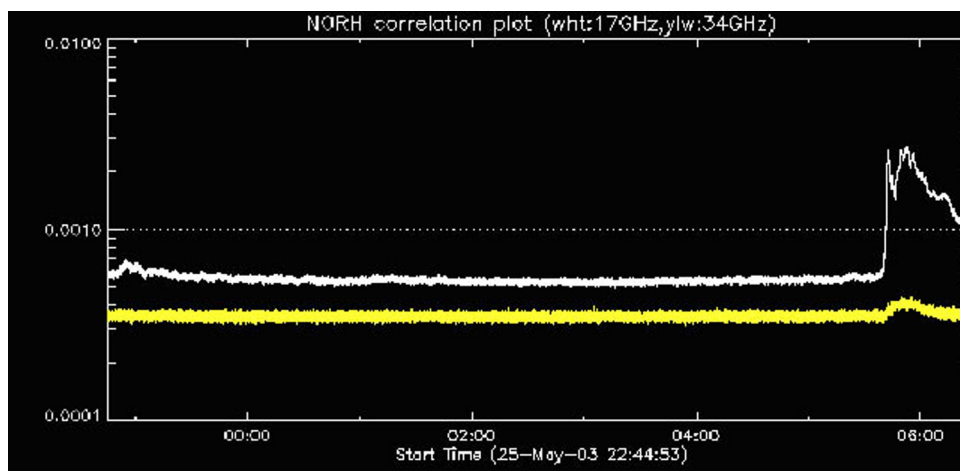
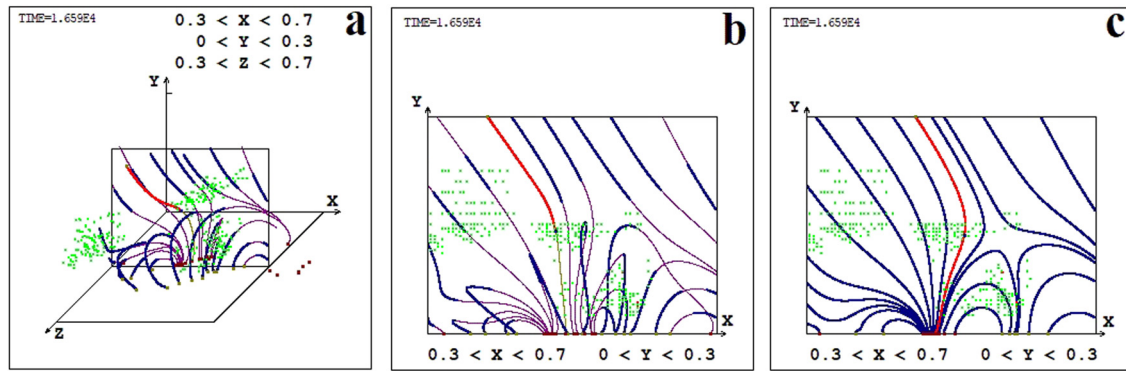
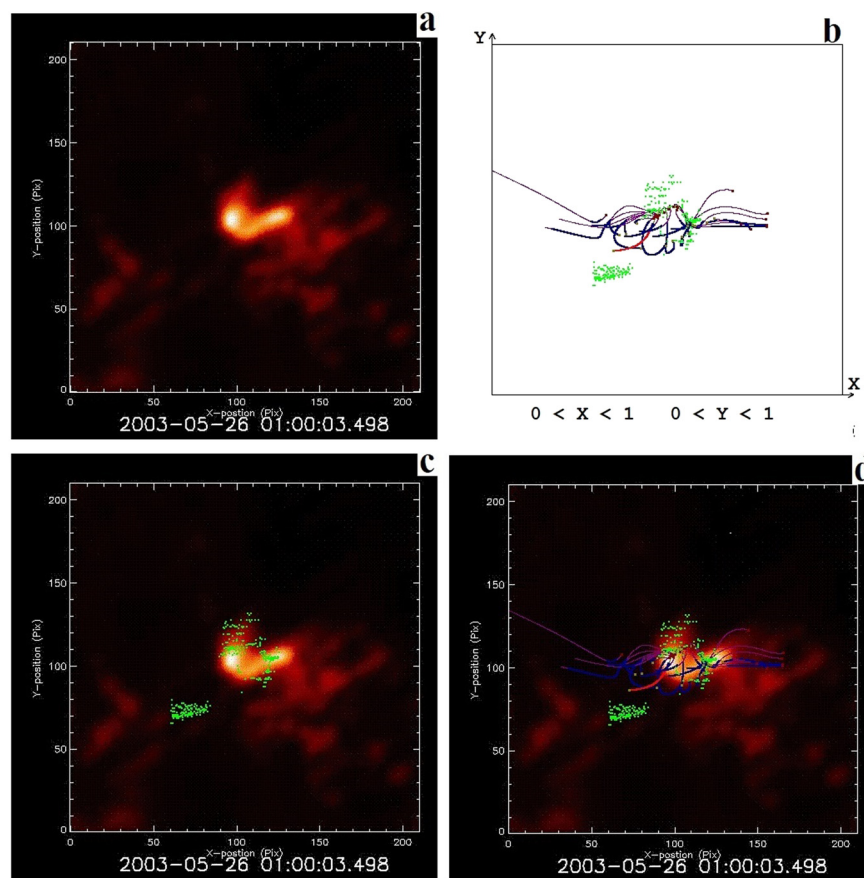


Figure 3: NoRH 17–34 GHz plot (25–26 May 2003) (from Nobeyama RadioHeliograph Team).

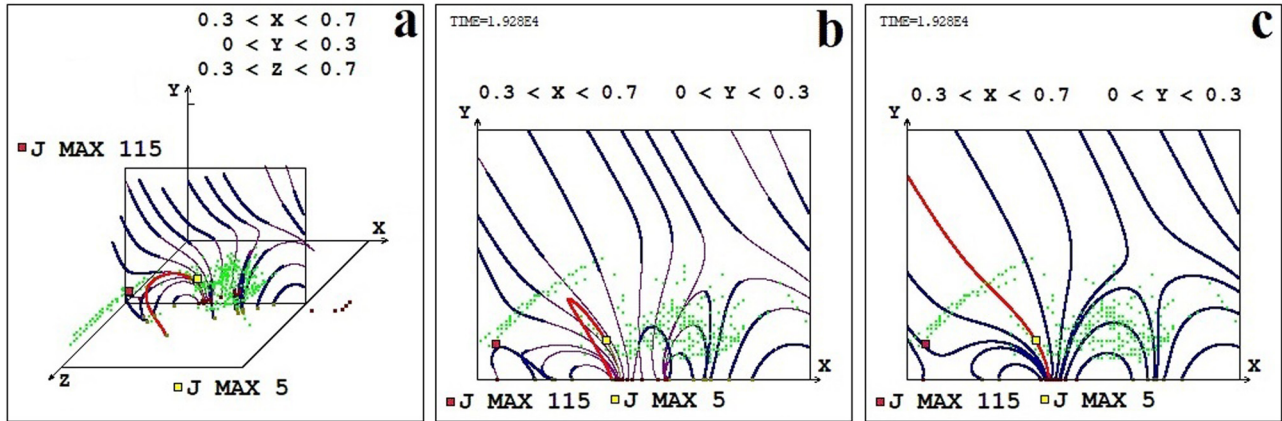




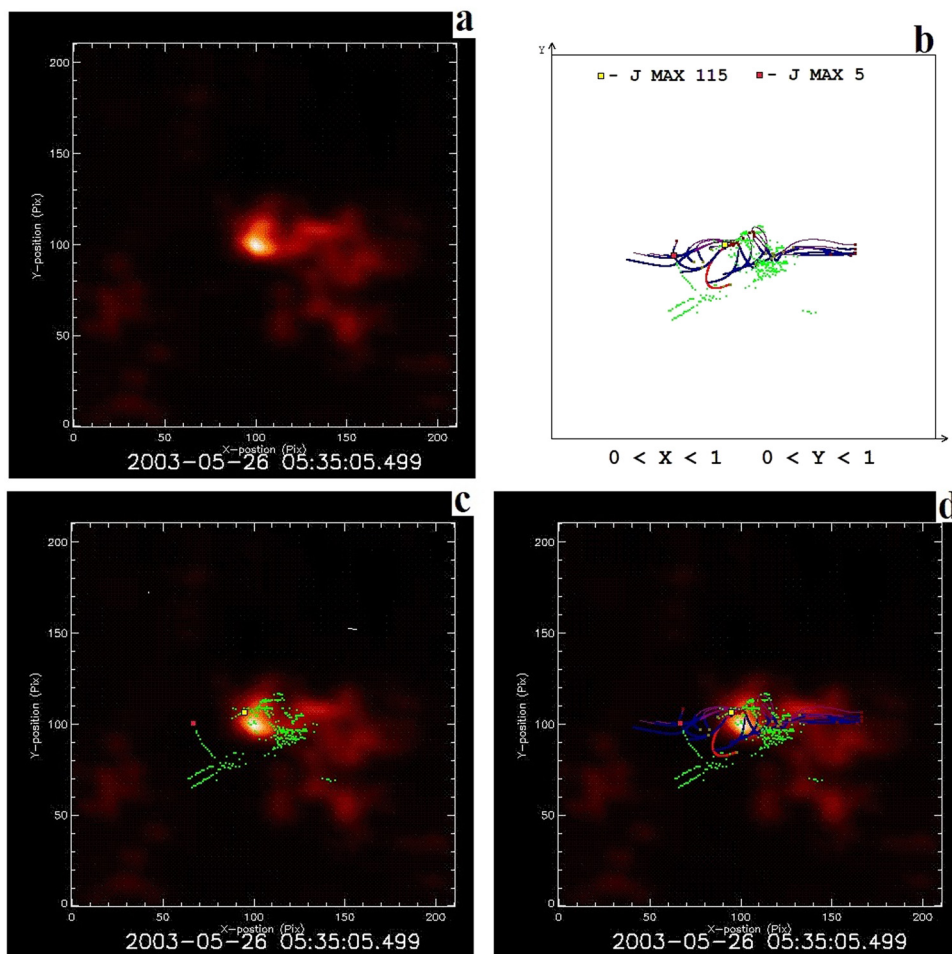
**Figure 4:** The results of MHD modeling and their comparison with observational data with the NoRH at the time 05/26/2003 01:00 (time from the beginning of the calculation is 1.1728 days,  $1.659 \times 10^4$  in dimensionless units). The positions of the current density maxima are shown in green. (a) Three-dimensional configuration of the magnetic field in the region ( $0.3 < x < 0.7$ ,  $0 < y < 0.3$ ,  $0.3 < z < 0.7$ ). (b) Projections of magnetic lines onto the central plane of the computational domain ( $0.3 < x < 0.7$ ,  $0 < y < 0.3$ ,  $z = 0.5$ ). (c) Flat configuration of the magnetic field in the central plane of the computational domain ( $0.3 < x < 0.7$ ,  $0 < y < 0.3$ ,  $z = 0.5$ ), represented by lines tangent to the projections of the magnetic field vectors on the central plane.



**Figure 5:** Comparison of the results of MHD simulation with observational data on the NoRH at 05/26/2003 01:00 in a square in the picture plane (perpendicular to the line of sight) in a square of size 400 mm  $\times$  400 mm (linear size of the photospheric boundary of the computational domain, taken as a unit of length). The center of the square is located on the solar disk in the center of the photospheric boundary of the computational domain at this moment in time. (a) The distribution of the intensity of radio emission at a frequency of 17 GHz, obtained with the NoRH. (b) The projections of the magnetic lines on picture the plane and the projections of the positions of the maxima of the current density, indicated by green dots. (c) Superposition of the positions of the current density maxima on the intensity distribution of radio emission at a frequency of 17 GHz. (d) Superimposing the projections of the magnetic lines and the positions of the current density maxima on the intensity distribution of the radio emission at a frequency of 17 GHz.



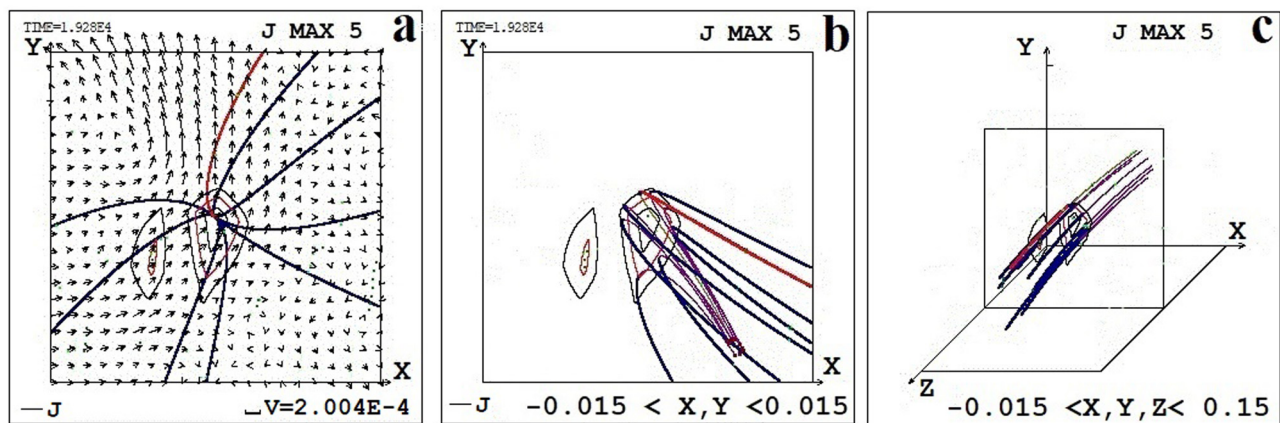
**Figure 6:** MHD simulation results and their comparison with observational data with the NoRH at 05/26/2003 05:34 (time from the beginning of the calculation is 1.3628 days,  $1.928 \times 10^4$  in dimensionless units). Graphical representations are similar to those shown in Figure 4, but different time (magnetic configurations a–c at the time 05/26/2003 05:34). The bold yellow dot shows the position of the 5th maximum, and the bold red dot shows the position of the 115th.



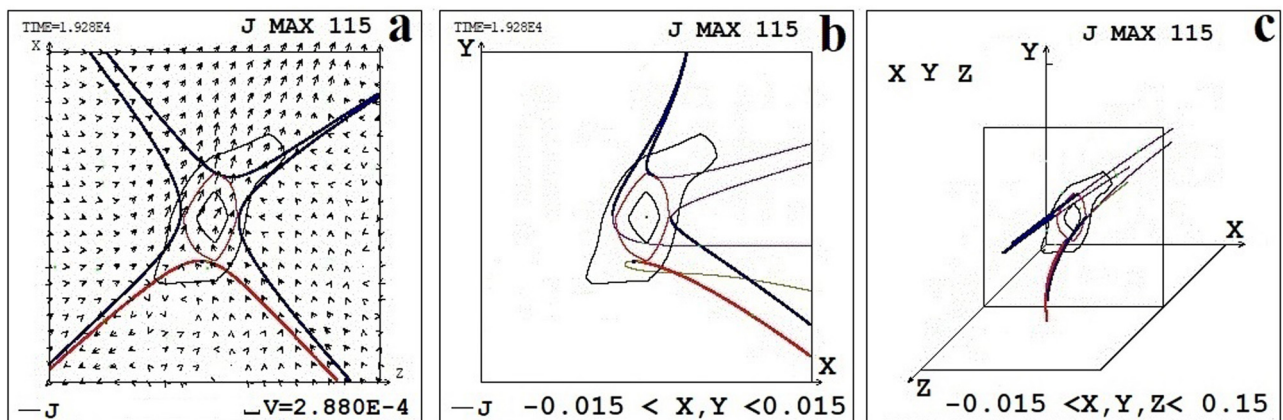
**Figure 7:** Comparison of the results of MHD simulation with observational data from the NoRH at 05/26/2003 05:34 in a square in the picture plane. Graphical representations are similar to those shown in Figure 5, but different time (projections a–d at the time 05/26/2003 05:34). The bold yellow dot shows the position of the 5th maximum, and the bold red dot shows the position of the 115th.

Figures 8 and 9 show the field configuration and plasma flow near the 5th and 115th current density maxima. The current density at the 5th maximum is 0.65 dimensionless units, and at the 115th maximum, 0.3 dimensionless units. However, due to grid effects, their relative role for flare activity can be incorrectly estimated based on the ratio of these current densities. To make it easier to visualize the configuration, one of the magnetic lines is highlighted, although it has no peculiarities compared to the other lines. The plasma flow deforms the field into a current sheet configuration, which is weakly expressed, since the computational grid is rather rough

(spatial step is 2 mm). In the vicinity of the 115th maximum, the configuration of the X-type magnetic field dominates; therefore, the magnetic energy of perturbations is accumulated most efficiently and the current sheet is more pronounced. However, towards the 115th maximum, a weak disturbance from the photosphere propagates, due to which the current density in it is low, and it does not situate into the bright region of radiation at a frequency of 17 GHz. However, a weak disturbance propagates from the photosphere towards the 115th maximum, due to which the current density in this maximum is low, and it does not situate into the



**Figure 8:** The configuration of the magnetic field and the plasma flow in a region with a linear size of 0.03 (12 mm) in the center of which the 5th maximum of the current density is located. The Z axis is directed along the magnetic field vector taken at the point of maximum current density. The plane (X, Y) perpendicular to the magnetic field vector is the plane of the configuration in which the current sheet is best expressed. (a) The magnetic field in the plane of the configuration, represented by lines tangent to the projections of the vectors of the magnetic field on the plane and the vector field of velocities, the scale of the velocity vector is shown. (b) Projections of magnetic lines onto the plane of the configuration. (c) Three-dimensional configuration of the magnetic field near the point of maximum current density.



**Figure 9:** The configuration of the magnetic field and the plasma flow in a region with a linear size of 0.03 (12 mm) in the center of which the 115th maximum of the current density is located. Graphical representations are similar to those shown in Figure 8, but for different J max (magnetic configurations a–c for J max 115).



bright region of radiation at a frequency of 17 GHz. A strong disturbance propagates to the 5th maximum from the photosphere, therefore this maximum is quite powerful, despite the fact that a diverging field dominates in its vicinity. The 5th maximum is located practically in the center of the bright region of radiation at a frequency of 17 GHz, and the maxima near the 5th one situated into the bright region.

## 5 Conclusion

- (1) During the M 1.9 flare on 05/26/2003 at 05:34, the configuration of the magnetic field above AR 10365 in the vicinity of singular lines is complex, and it is almost impossible to determine the appearance of a singular line and the current sheet from the 3D configuration. The points of the current density maximum, located on the singular lines of the magnetic field, which is obtained by MHD simulation, are found using a specially developed search system. The imagination of the behavior of the magnetic field near the singular line is best given by the configuration in the plane perpendicular to the singular line (perpendicular to the magnetic field vector, which is taken at a point on the singular line).
- (2) Often, at an X-type magnetic field configuration near a singular magnetic field line a diverging magnetic field is superimposed that can dominate, so that the resulting configuration does not resemble an X-type field. However, due to the presence of the X-type configuration in the superimposed fields, MHD simulation shows the formation of a current sheet or a tendency to form a current sheet due to the deformation of the magnetic field by the plasma flow.
- (3) The found points of the current density maxima are arranged in groups of several tens of points, which apparently indicates the possibility of the appearance of a large number of closely spaced singular lines. In the complex magnetic field of the solar corona, the appearance of a large number of singular lines and current density maxima located on them is quite possible; however, as a result of the calculation of such maxima, too many of them could appear in comparison with their number in a real situation due to the too large spatial step of the computational grid for the selected low ordinary and magnetic viscosities.
- (4) The location of a large group of current density maxima, in which current sheets should appear in a real situation, in a bright region of radio emission at a frequency of 17 GHz, while the largest maximum in this group (the 5th maximum of the current density) is located practically in the center of the bright region, supports mechanism of a solar flare based on the release of energy accumulated in the magnetic field of the current sheet. These maxima were located at heights of 15–20 mm, and the 5th maximum was at an altitude of 18 mm.
- (5) At the current density maxima located in the bright region of radiation at a frequency of 17 GHz, a dominant diverging magnetic field is superimposed on the X-type configuration. However, due to the presence of an X-type configuration among the superimposed fields, under the influence of a disturbance propagating from the photosphere, magnetic energy accumulates in the vicinity of singular lines, current density maxima arise, and the plasma flow in a real situation should deform the field into a current sheet configuration.
- (6) Another group of current density maxima, in which the 115th maximum is the largest, was located in the corona with such a magnetic field that the X-type field configuration dominated near singular lines, and therefore the accumulation of magnetic disturbances near such singular lines should be most effective. However, any significant perturbation does not propagate into this region of the corona from the photosphere. In such a situation, the 115th and the surrounding current density maxima do not located into the bright region of the flare radiation at a frequency of 17 GHz.

MHD simulation in a problem statement close to ours was carried out in the study by Jiang *et al.* (2016) above AR 12192. The formation of a current sheet was shown at the site of the flare observed in the 94 Å line of the ion of multiply ionized iron FeXVIII, which appears at a temperature of 6.3 MK. In AR 12192, powerful subphotospheric magnetic field sources were located in such a way that the configuration of the X-type magnetic field near the singular line, in contrast to the AR studied in our work, was in the region of a large size in corona. Therefore, to determine the position of the singular line and the current sheet formed in it, a graphical system for searching for the flare positions was not needed, which in our case cannot be dispensed with.

MHD simulations carried out in the study by Jiang *et al.* (2016), as well as our MHD simulations, showed that no magnetic ropes appear in the corona above the AR.



At present, the study of alternative mechanisms of solar flares, based on the accumulation of flare energy in the magnetic field of the rope, has become widespread. This mechanism was studied by simulation above an AR, in which the initial magnetic field in the corona contained an unstable or even nonequilibrium rope. The rope could be inserted in different ways, most naturally it was obtained in a force-free magnetic field obtained for a vector magnetic field observed in the photosphere, as it was done in the study by Jiang *et al.* (2018). MHD simulation showed the development of the flare process as a result of the instability of the rope, but it is impossible to explain how the unstable rope could appear, why it did not destroy due to instability during the formation process. The boundary magnetic field observed in the photosphere does not have to correspond to a force-free field; magnetic forces and plasma movements in a field may appear in the corona, which does not necessarily have to contain magnetic energy for a flare. If, nevertheless, an unstable rope causing a flare can somehow appear in the corona, then this should be obtained as a result of MHD simulation. The present work and all the above studies lead to the conclusion that it is necessary to carry out MHD simulation above the AR, which should begin several days before the flare, when the energy for the flare has not yet been accumulated in the corona. Such simulation is necessary to study the processes during a flare, regardless of its mechanism.

Thus, solar flare mechanism, based on the accumulation of energy in current sheet (in the neighborhood of X-type singular magnetic line), proposed by Syrovatskii and other well-known researchers was confirmed for first flare AR 10365 from the obtained results of MHD modeling in real scale of time with high precision.

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