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Solar Flare Location on the Extended Arc of Magnetic Lines with Increased Current Density, Obtained by Analyzing the Results of MHD Simulation

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Abstract

The appearance of extended surface of magnetic lines with increased current density (extended current sheet) in solar corona can solve the problem of the coincidence of the positions of flares found from the results of MHD simulation with the observed positions of flares. The compare of magnetic configuration near such a surface with observed flare emission show that flare energy release can occur not in the position of current density maximum, but in the place, were the current density is rather large and where the magnetic field configuration promote the flare instability development. For more convenient search of flare positions to study the solar flare mechanism, it will be better to modernize the existing graphical system for searching for flare positions taking into account obtained results about location of flare instability.

Keywords: Solar flare; current sheet; magnetohydrodynamic simulation, singular line.

1. Introduction

Primordial energy release of the solar flare takes place in the solar corona at the altitude 15 000 km - 70 000 km (1/40 - 1/70 of the Solar radius), which is proofed by appearance of a source of flare thermal X-ray emission on the limb [Lin et al., 2003] and other numerous observations. The slow accumulation of energy for a solar flare in a stable magnetic field configuration in the corona, and then its transition to an unstable state, explains the physical mechanism, based on the accumulation of energy in the magnetic field of the current sheet formed in the vicinity of a singular line of magnetic field due to appropriate directions of magnetic forces $j \times B$ [S. I. Syrovatsky 1966; Bratenahl and Hirsch 1966]. During the process of quasi-stationary evolution, the current sheet transfers into an unstable state.

The fast release of magnetic energy of the current sheet leads to the observed manifestations of a flare, which are explained by the electrodynamic model of a solar flare proposed by I. M. Podgorny [Podgorny et. al 2010]. The occurrence of hard X-ray radiation on the solar surface during a flare is explained by the acceleration of electrons in field-aligned currents caused by the Hall electric field in the current sheet, directed along magnetic lines exiting from the current sheet in the direction of the solar surface. The electrodynamic model of solar flare uses analogies with the electrodynamic model of substorm, previously proposed by its author based on measurements on the ”Intercosmos-Bulgaria-1300” spacecraft [Podgorny et. al 1988].

Since it is impossible to obtain the configuration of the magnetic field in the corona from observations, to study the flare situation it is necessary to carry out MHD simulations in the solar corona. The magnetic field measured at the solar surface was used for setting the boundary condition. When setting the problem, no assumptions were made about the mechanism of the solar flare. To study the physical mechanism of a solar flare, calculations must begin several days before the flare, when magnetic energy for the flare has not yet accumulated in the corona. Setting of problem and developed methods including stabilization of numerical instability, which appears in first turn near the boundary of computational domain, are described in [Podgorny and Podgorny 2023].

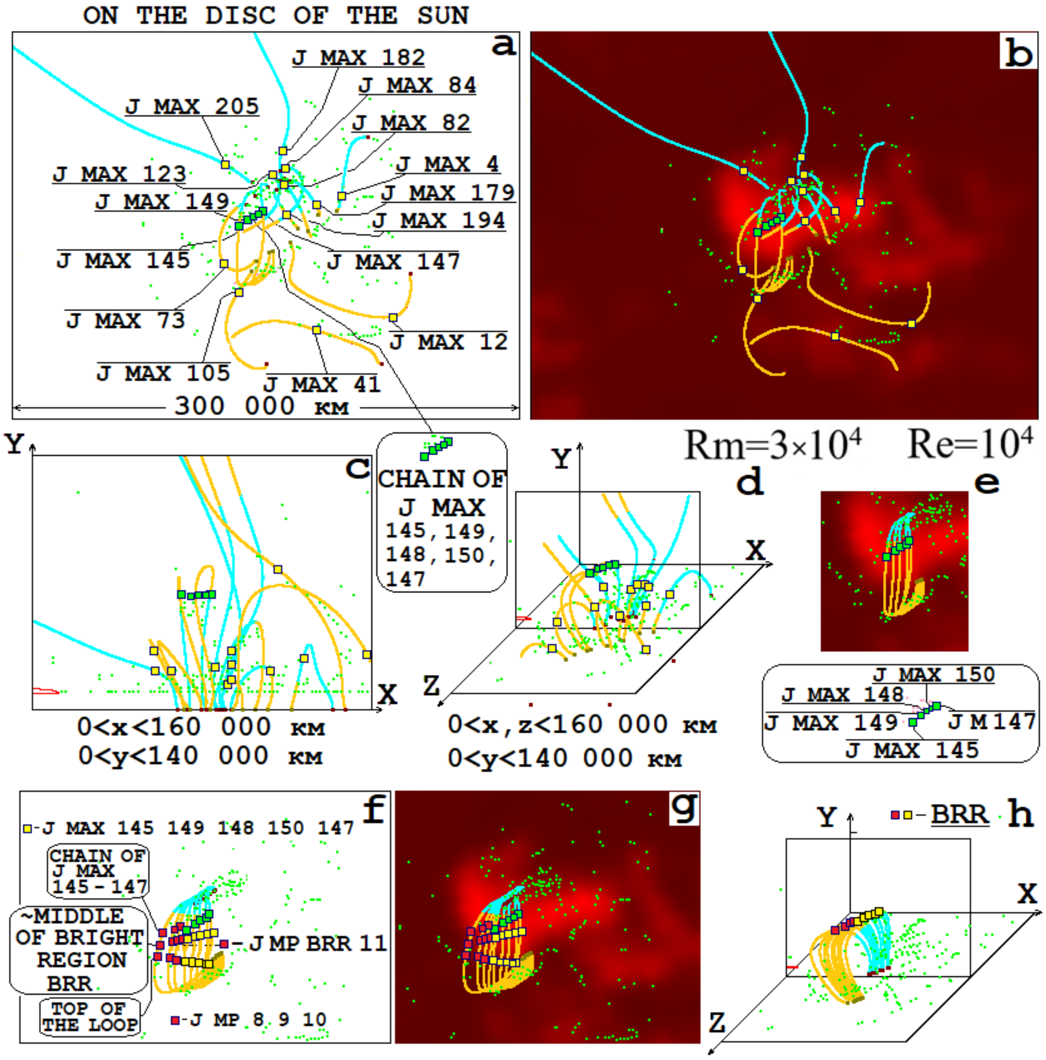

Figure 1. *The magnetic field configuration is represented by magnetic lines passing through the selected current density maxima. The projections of lines onto the picture plane perpendicular to the line of sight (a) with superposed distribution of microwave radio emission at a frequency of 17 GHz, obtained on the solar disk using the Nobeyama radioheliograph (b), onto the central plane of the computation domain (c), in 3D space (d). Arcade of lines (f, g, h) passing through the chain of maxima shown by green points. In (e, f, g, h) the lines passing through plane maxima in plane normal to magnetic field vector on the top of the loop are added.*

The magnetic field configuration obtained by MHD simulation is so complex that it is often impossible to determine the positions of singular lines and the current sheets appearing near them. For this purpose, a graphical search system [Podgorny and Podgorny 2013] was developed, based on determining the positions of the current density maxima, which are assumed to be achieved in the centers of the current sheets (according to presented here results this assumption is not always fulfilled, so the graphical search system should be corrected). The current density maxima are located on singular lines of the magnetic field. Magnetic forces **j**×**B**, creating a current sheet configuration, are determined by the current component along the singular line and the magnetic field components in the plane perpendicular to the singular line (the current sheet configuration plane, in which field

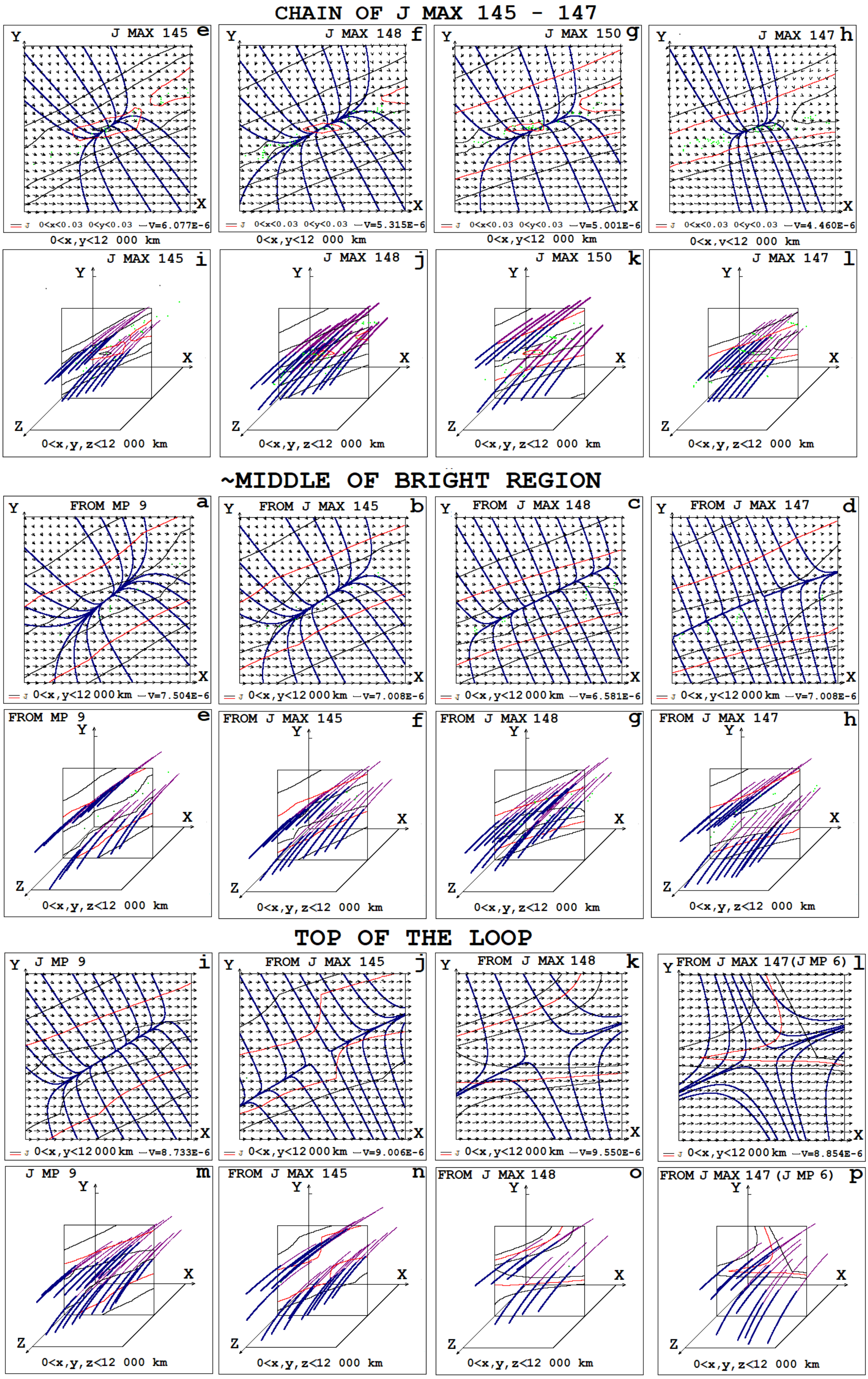

Figure 2. *Magnetic field configurations in small regions of 12 Mm.*

configuration of the current sheet is mostly pronounced). Therefore, the main role in the formation of current sheets is played by plane magnetic field configurations, i.e. lines tangent to the projections of the magnetic field vectors onto the configuration plane.

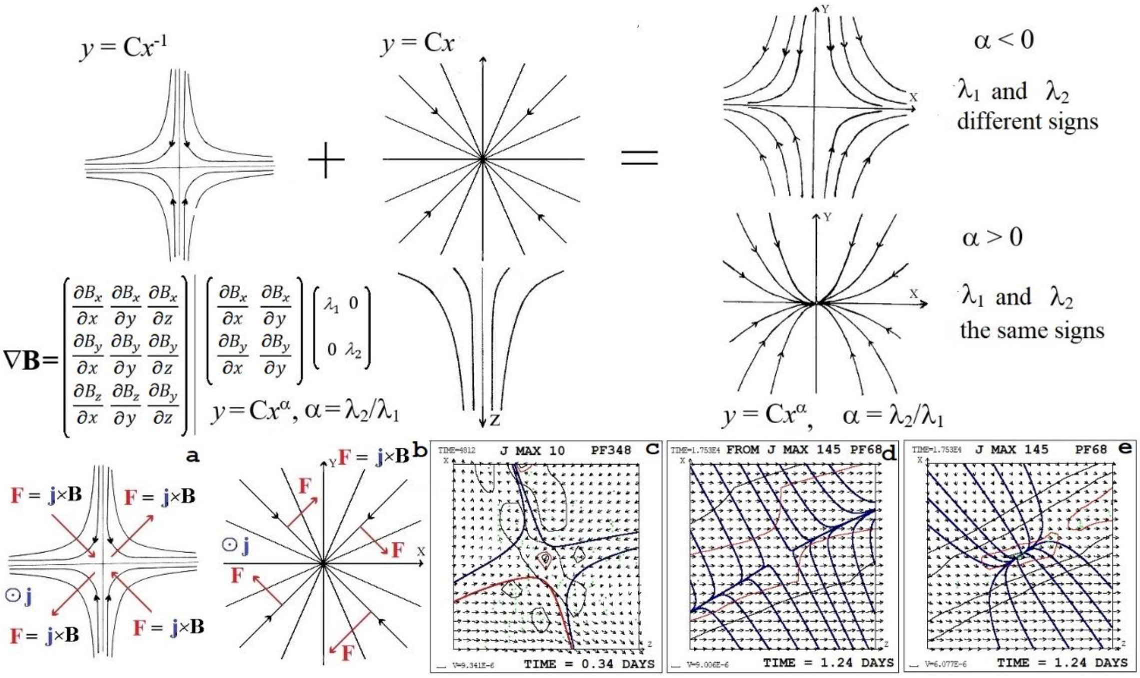

Figure 3. *Overlay of a diverging magnetic field on an X-type field near a singular line.*

2. Magnetic configuration near extended surface with increased current density

An analysis of the positions of current density maxima and magnetic field configurations in their vicinity, carried out for a number of flare and pre-flare situations [Podgorny et. al 2022, 2023; Podgorny and Podgorny 2023], showed the location of some maxima with magnetic field configurations promotable for the occurrence of a flare in the region of bright flare radiation. However, at the same time, maxima with such properties also occur outside the bright region of flare emission, and in the bright region there are not very many such maxima compared to their total number. To solve this problem, the pre-flare configuration of the magnetic field above the active region AR 10365 on May 26, 2003 at 02:32:05, three hours before the M 1.9 flare, was studied. In this moment the energy for solar flare is accumulated in the magnetic field and plasma of solar corona is heated by currents which creates this magnetic field. The results of MHD simulation were compared with observations of microwave radio emission at 17 GHz obtained from the Nobeyama Radioheliograph (NoRH). Magnetic field configuration is represented in Figure 1 by lines passing through maxima of current density with the numbers 145, 147, 194, 179, 4, 73, 105, 41, 12, 205, 123, 82, 84, 182. All current density maxima found by the graphical search system for flare positions are numbered in descending order of the current density value at the maximum. The current density maxima with numbers 145, 149, 148, 150 and 147 marked by green present the chain of maxima in the picture plane perpendicular to the line of sight which is situated near the bright region of pre-flare emission. To understand occurrence of bright region with intensive pre-flare energy release the magnetic lines passing through maxima of the chain are presented by their projections on the picture plane (Figure 1 e-g), which are situated mostly into the bright region, and by arcade in 3D space (Figure 1 h).

Figures 2a-h shows the plane (Fig. 2a-d) and three-dimensional (Fig. 2e-h) configurations near the chain maxima in a square and in a cube of 12,000 km. The two-dimensional region is a square of 12,000 km in size with the center at the point of the selected current density maximum, with the plane of the square located perpendicular to the magnetic field vector at the point of the selected maximum (plane of the current sheet configuration perpendicular to the magnetic line passing through the point of the selected maximum). The three-dimensional region is a cube 12,000 km in size centered at the point of the selected maximum of current density, so that the two-dimensional region is the central plane of this cube, i.e. a plane passing through the center of the cube parallel to two faces of the cube.

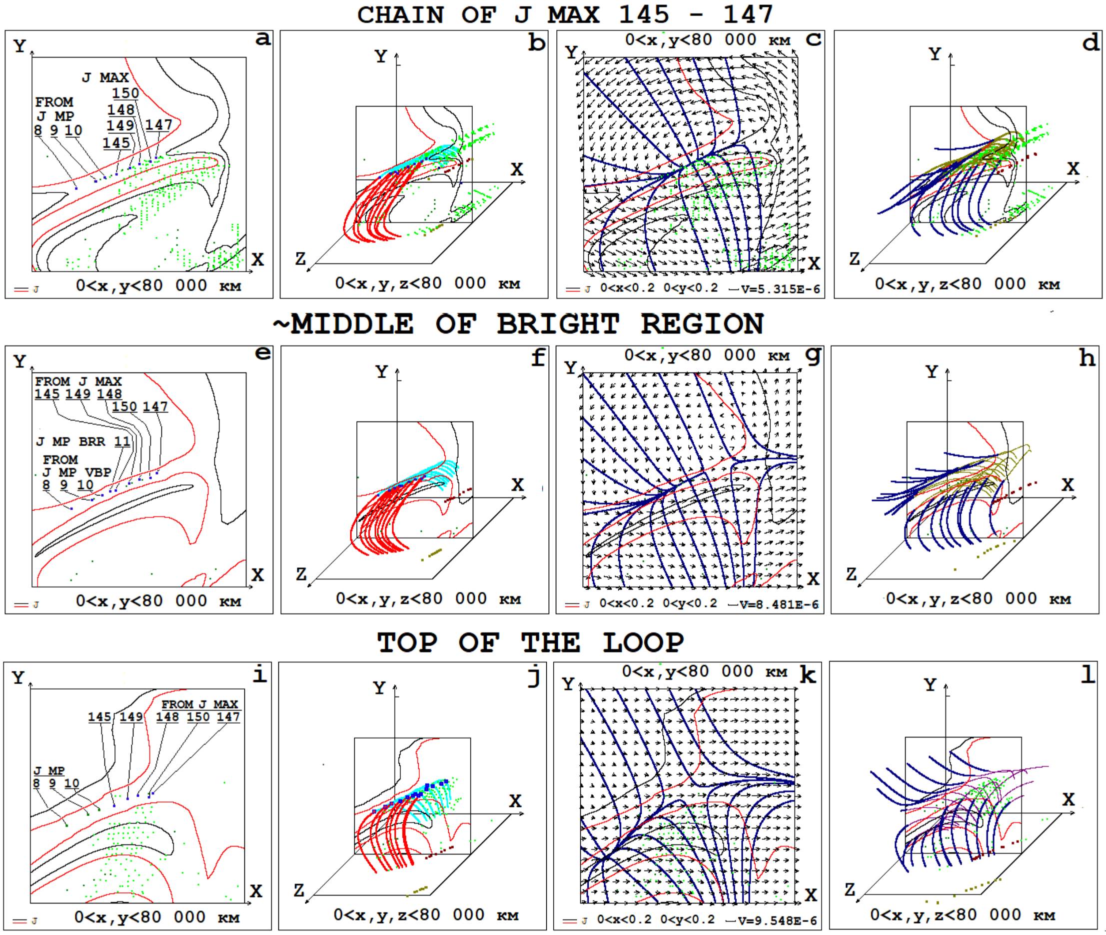

Figure 4. *Magnetic field configurations in large regions of 80 Mm.*

In Figures 2a-d the magnetic field strongly divergent in the plane of current sheet configuration (field appearing in magnetic traps of the mirror cell type) is superimposed on the X-type magnetic field. Variants of such superposition in which the X-type field or divergent magnetic field is dominated are shown in Figure 3. For configurations in Fig. 2a-d similar to Fig. 3e the magnetic forces cause plasma rotation around singular line (Fig. 3a), hindering the formation of current sheet and appearance of flare instability in formed current sheet. In three-dimensional configurations (Fig. 2e-h), the field lines do not diverge much along the singular line, which means a comparatively large longitudinal component of the magnetic field stabilizing the explosive instability. Therefore, these configurations in vicinities of chain maxima (Figures 2a-h) do not have properties that could significantly promote the flare release of energy. It became clear why chain of maxima is situated near the boundary.

The chain maxima are located close to each other (Fig. 1) and the field configurations in their vicinity are very similar (Fig. 2a-d и Fig. 2e-f), so that an assumption arises that all the chain maxima belong to the same current sheet of considerable width (~50,000 km), i.e. an extended surface with an increased current density. This assumption is confirmed by the study of plane and three-dimensional configurations in a square and in a cube with a larger size of

80,000 km with the center at the 148th maximum (Fig. 4a-d). The square is the central plane of the cube. In the square of a large size the intersection points of the magnetic lines passing through the chain maxima with the plane and also lines of equal current density are shown (Fig. 4a). Magnetic lines in a cube passing through the chain maxima form an arcade (Fig. 4b). The plane and three-dimensional configurations in large areas are shown in Figures 4c, d.

Configurations in small regions of 12 Mm in size with centers at the points of the arcade above the middle of bright region (Fig. 2 i-p) and at the top of the arcade (Fig. 2 q-x), as well as in large regions of 80 Mm in size with centers at the points above the bright region (Fig. 4e-h) and at the top of the arcade (Fig. 4i-l), were constructed similarly. The intersection points of the arcade magnetic lines with the central planes of large regions of 80 Mm in size were chosen as the centers of small regions of 12 Mm in size. To the magnetic lines of the arcade passing through the maxima of the chain, magnetic lines (Fig. 1f-h) passing through the plane maxima of the current density located in the central planes of the large-size regions of 80 Mm in the middle of the bright region and at the top of the arcade are added. The results presented in Figures 2, 4 show that the configurations in both the small 12 Mm and large 80 Mm regions in the middle of the bright pre-flare region and at the top of the arcade are more promotable for the occurrence of flare instability than in the chain of current density maxima.

3. Discussion and conclusion

The performed analysis of magnetic configurations provides an explanation for the heating of the plasma in the bright pre-flare region, despite the absence of a chain of current density maxima near the middle of this bright region. In the future, these results will need to be refined by performing more accurate calculations and analysis, and then used to modernize the graphical system for searching for the positions of solar flares.

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