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Comparison of Kinematics of the Solar Eruptive Prominence and a Spatial Distribution of the Magnetic Decay Index

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Abstract.

Theoretical studies of magnetic flux rope instabilities, designed to explain filament eruptions, indicate that the loss of equilibrium may develop when the surrounding magnetic field decreases sufficiently rapid with height. The decay index, a parameter that reflects the decrease of magnetic field, is a useful instrument for predicting the behavior of filaments. In our study, we perform potential extrapolation to obtain spatial distribution of the decay index in the coronal space, identified with an eruptive prominence. Analysis of time dependent height profile of the prominence revealed, that its speed increased when the prominence reached height with certain values of the computed decay index.

Introduction

Solar prominences are extended concentrations of coronal matter that is much denser and cooler than its surroundings and are clearly distinguishable when they are seeing above the solar limb. Because of the same reason they manifested as darker formations while observed in projection on the disk. In the latter case they are called filaments. Solar prominences may exist in a stable state for many days and then suddenly start to accelerate in an upward direction. If new state of equilibrium cannot be achieved at higher altitudes and rapid upward motion continues, they may produce a coronal mass ejection (CME).

Coronal magnetic field dominates over gas pressure, so motions of highly conductive plasma are allowed along force lines of the magnetic field. Thus, gradual formation of dense concentrations of coronal plasma, suspended in a stable state on magnetic force lines, is possible in regions, where magnetic lines has curvature which vector is directed upward. In the study [Kuperus M. and M.A. Raadu, 1974] was introduced a model of a prominence in which magnetic configuration, able to confine plasma, was created by linear horizontal electric current in the coronal space and its mirror reflection with opposite sign below the photosphere. In this model gravitational force, acting on dense matter in the prominence, is counterbalanced by the repulsive Lorentz force between currents with opposite directions. This is in agreement with the observations revealing that plasma inside prominences often takes twisted orientation, thus resembling magnetic flux ropes and indicating the presence of electric currents.

In the study [Van Tend W. and M. Kuperus, 1978] the model of [Kuperus M. and M.A. Raadu, 1974] was enhanced by introducing background coronal magnetic field. The authors investigated state of equilibrium of electric current, influenced by ambient magnetic field, and found that instability against small vertical displacements will develop when magnetic field decreases sufficiently rapidly with height. The rate of the magnetic field decrease may be represented by a parameter that is called magnetic decay index. Theoretical model for prominence eruption was further addressed in the paper [Kliem B. and T Torok, 2005], where authors investigated state of equilibrium of ring current anchored on the photosphere surface. The authors termed the loss of equilibrium for such configuration of the current as torus instability. In the studies [Filippov B.P. and O.G. Den, 2001], [Fillipov B.P. et.al., 2014] authors considered real observational data and by applying potential extrapolation showed that prominences exist in a stable state below the altitude at which instability of linear current may develop.

In our study, we consider a prominence that erupted above the solar limb. We use observational data, provided by Atmospheric Imaging Assembly (AIA) and Heliospheric and Magnetic Imager (HMI) instruments onboard Solar Dynamics Observatory (SDO) spacecraft [Pesnell W.D., B.J. Thompson, P.C. Chamberlin, 2012]. We compare kinematics of the eruptive prominence and spatial distribution of the magnetic decay index in the coronal space, obtained with use of potential extrapolation.

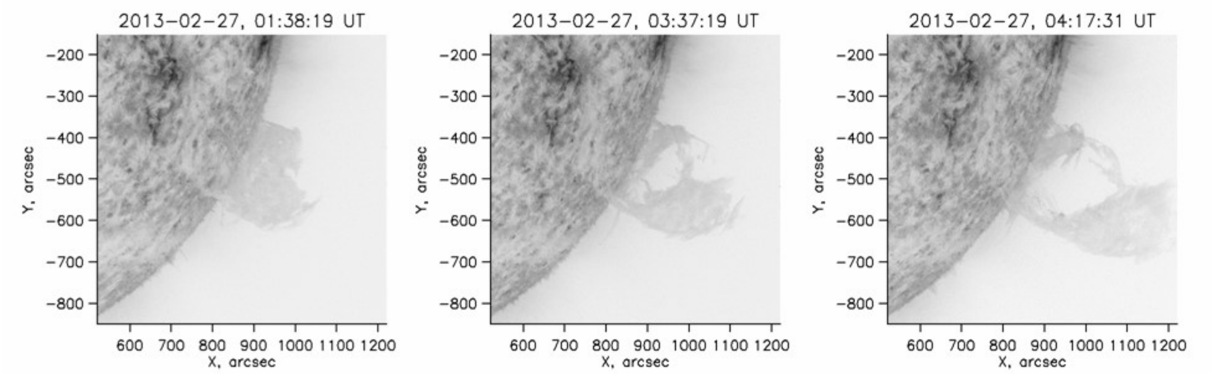

Fig. 1 SDO\AIA 304 Å images of the eruptive prominence.

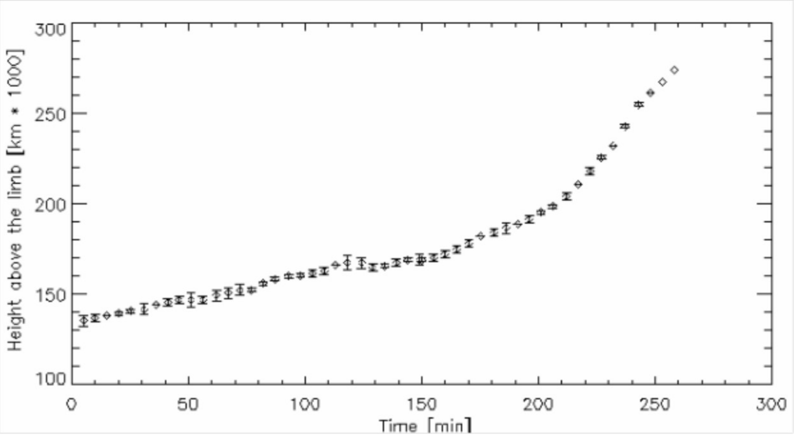

Fig. 2 Time-dependent height profile of the prominence's apex above the limb. The beginning of the timeline corresponds to February 27, year 2013, 0:00 UT.

Eruptive prominence

As an object for our study we chose a prominence outside active region that erupted on February 27, year 2013 when it was located above the South-Western solar limb (Fig. 1) According to catalog [Gopalswamy N. et al., 2009], the eruption was followed by a CME with average speed equal to 622 km/s. The position of the eruptive prominence allowed to track its apex by analyzing complete sequence of the SDO/AIA 304 Å images with ~5-min cadence, while prominence stayed in the instrument's field of view, and to build time-dependent height profile of the apex above the limb. Comprehensive explanation of this procedure is presented in the study [Tsvetkov Ts. and N. Petrov, 2018] and here we used some of the results from this paper (Fig. 2). By inspecting the obtained profile, we determined that the prominence had lost the equilibrium when its apex reached height of 180-190 Mm.

Magnetic field reconstruction

Coronal magnetic field is reconstructed using Green’s function based potential extrapolation. The extrapolation code was developed by the authors of the present study and is designed to work in spherical geometry. As input boundary conditions SDO/HMI vector magnetograms with resolved pi-ambiguity is used, that allowed to calculate radial component of the magnetic field. Extrapolation is performed using magnetogram obtained on February 25, 0:00 UT. We used data, obtained several days before the eruption, because magnetograms that are too close to limb, obviously, have inappropriate quality due to projection effect. We assume, that large-scale magnetic structures outside the active region are rather stable and probably will have similar configuration after several days. Our extrapolation code works with predefined areas of the photosphere surface. For the case under consideration computational domain on the photosphere level is about 700 by 500 Mm, its height is 300 Mm and spatial resolution is 3 Mm. Outside the computational domain photosphere radial magnetic field considered equal to zero.

Magnetic decay index

Following [Kuperus M. and M.A. Raadu, 1974], to predict the prominence eruption it is necessary to know how fast coronal magnetic field decreases with height. This can be evaluated by using a parameter that is called magnetic decay index:

$$n = -\frac{\partial \ln(B_t)}{\partial \ln(h)} \qquad (1)$$

here B_t – is transversal component of the ambient magnetic field, h – is the height above the photosphere. For a straight linear electric current estimated critical threshold is n=1. In the regions where magnetic decay index is greater than unity electric current of such configuration cannot be confined by magnetic field and start to ascend leading to the prominence eruption. In the study [Kliem B. and T. Torok, 2005] was determined that critical value of magnetic decay index for ring current is n=1.5.

Comparative analysis

Electric current in a stable state tend to be oriented along neutral line of the external magnetic field at each particular height, due to horizontal Lorentz forces vanishes there. Fig. 3 demonstrates that outside nearby active regions 11673, 11676 and 11677 neutral line of the extrapolated potential magnetic field corresponds to the prominence quite well. According to the extrapolation results different parts of the prominence located at different altitudes. Based on the obtained results we assume that the prominence ascended along the surface, formed by neutral lines, to the height where instability developed. Thus, regions of interest where spatial distribution of the magnetic decay index must be considered are in close proximity to the reconstructed neutral line.

Information on 3D structure of the extrapolated magnetic field allows one to calculate magnetic decay index everywhere inside the computational domain, using equation (1). Fig. 4 represents spatial distribution of the magnetic decay index at several particular heights. To avoid projection effects, the observer’s position was relocated to the point above the center of the computational domain. According to the obtained results magnetic decay index increased monotonically in the region around the neutral line, identified with the eruptive prominence. From SDO/AIA 304 Å images we estimate that transverse size of the prominence by the onset of the eruption was up to 100 Mm. Assuming the electric current to be located near prominence’s axis, we can subtract half of transverse size from previously estimated height of the apex of the prominence equal to 180-190 Mm. Obtained value is close to the height where magnetic decay index exceed critical value of 1.5, that is characteristic for the torus instability, over a considerable length of the neutral line.

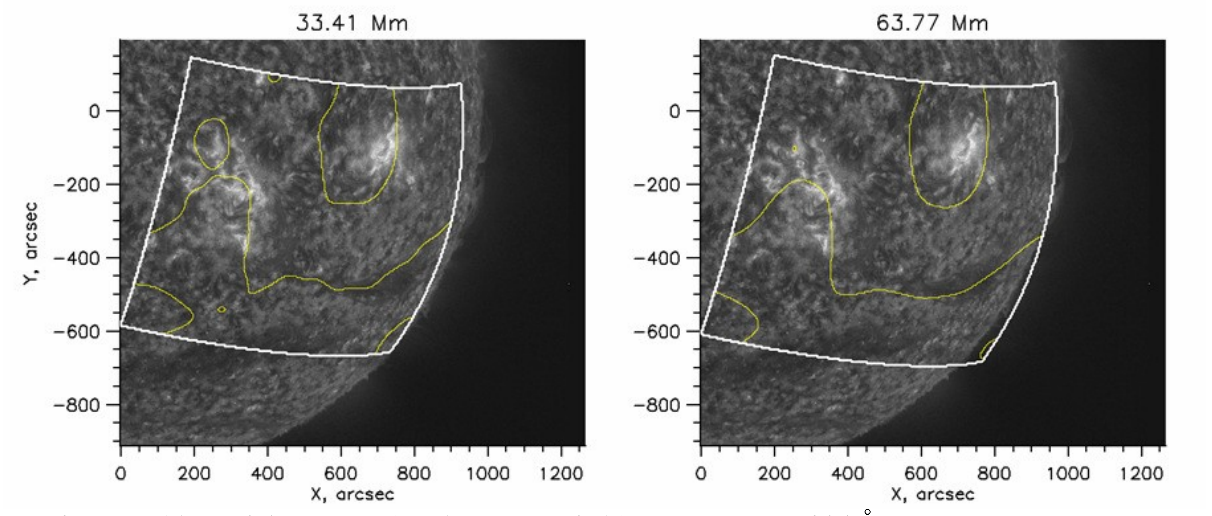

Fig. 3 Neutral line of the extrapolated magnetic field over HMI/AIA 304 Å image on February 25, year 2013, 0:00 UT. Yellow contours – neutral line. Thick white contour marks boundary of the computational domain. Neutral line is shown for two spherical layers above the photosphere surface. Heights of the layers are given in titles.

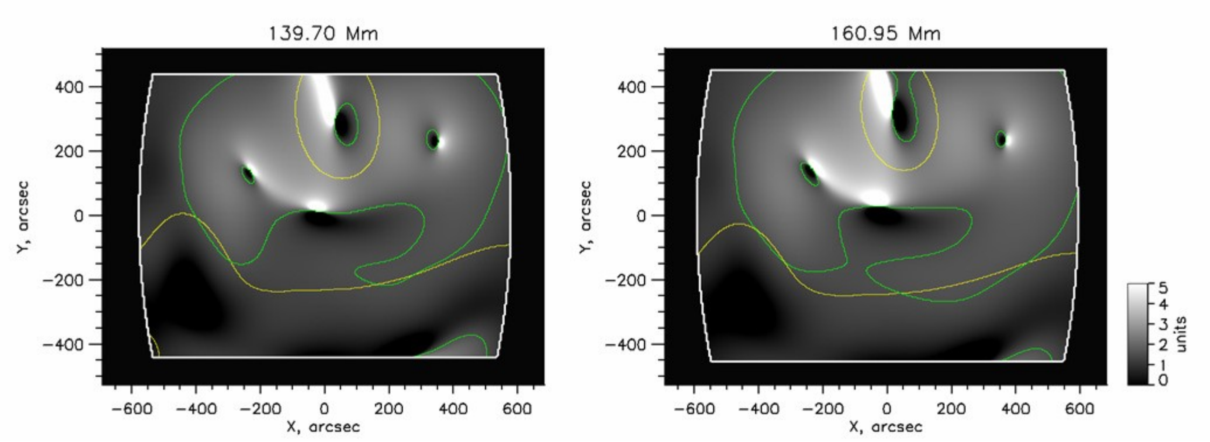

Fig. 4 Spatial distribution of the computed magnetic decay index at two heights above the photosphere, given in titles. Green contours correspond to decay index value equal to 1.5. Yellow contours – neutral line. Thick white contour marks boundary of the computational domain. Minimal and maximal values of the magnetic decay index are limited to 0 and 5.

Conclusions

The eruption of a solar prominence located above the solar limb is considered. Comparative analysis of kinematics of the prominence and spatial distribution of the magnetic decay index revealed that the prominence had lost its equilibrium when electric current, identified with approximate prominence's axis, reached height with critical values of the magnetic decay index equal to 1.5. That indicates the torus instability as possible mechanism of the prominence eruption.

Acknowledgment

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