DYNAMICS AND STABILITY OF HELICOIDAL MAGNETIC CONFIGURATIONS IN THE SOLAR CORONA

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Abstract. The internal structure of thirty prominences exposing helicoidal-like shapes is studied. The Hα fine structure threads reveal that the magnetic field permeating the prominence can be described in the form of an uniform twist configuration. One case of twist transport into the expanded part of the magnetic flux tube containing the prominence body is described. Prominences with strongly twisted field lines tend to rise upward and stretch themselves through a series of quasi-equilibrium states, avoiding a violent relaxation of the magnetic field configuration. A classical eruption process takes place if during such a quasistatic evolution the critical conditions for the eruptive instability are reached.

1. Introduction

The fine structure of prominences as observed in the Hα line discloses the magnetic field configuration since the "frozen-in" condition is fulfilled, and so a study of prominence's morphology can provide valuable informations about the nature and dynamics of the magnetic fields embedding the cold prominence plasma (Vršnak, 1992). We inspected Hα configurations of many prominences to select cases showing well defined helical-like structures. In total, thirty active region and quiescent prominences, appearing as a bundle of helicoidal fine structure threads, were then studied to establish the properties of the individual internal structure and its dynamics.
2. Internal Structure and Dynamics of Plasma Flows

In the cases with several threads wound around a prominence’s axis at different radii, we established the dependence of the pitch angle (θ) and the pitch length (λ) on the radial distance (r) from the axis. The analyzed cases indicate that magnetic structures tend to achieve an uniformly twisted configuration, i.e. \(\text{tg} \theta = X = 2\pi / \lambda - r\) is valid (Vršnak et al., 1988). The best observed case was the prominence which erupted on August 18, 1980 (Vršnak et al., 1993). In the pre-eruptive phase the prominence had the form of a curved flux tube, anchored at footpoints in the chromosphere and expanded at the summit. The twist was transported into the expanded parts of the prominence body. The measured values for the pitch angles (θ) and the ratios of the tubes radii (R) in the contracted and expanded parts of the prominence were X=\(\text{tg} \theta\), =0.8±0.2, X=\(\text{tg} \theta\), =3.5±0.5 and R/R⊥=2, respectively. So, one finds the ratio of pitch lengths as λ/λ⊥=0.5±0.2, which demonstrates the process of the twist transport along the prominence axis from a narrow part of the tube into a radially expanded part of the tube.

Usually, more or less intense mass flows are observed along the fine structure threads of active prominences, implying that the hydrostatic approximation is not valid. The motions along the threads with velocities in the order of \(\nu=100\) km/s are controlled and channelled by the magnetic field, providing an estimate \((\nu^2B^2/\mu_0)\) of the lower limit to the magnetic field strength about \(B>20\) G and an estimate of the amount of the total axial electric current in the order of \(I=10^{11}\) A. There are three classes of plasma flows along the fine structure threads: a) the ones dominated by the gravitational acceleration; b) those deviating from gravitational acceleration; c) constant velocity motions (Vršnak, 1984; 1985). As the transpositions of the cold plasma have no influence on the morphology of these prominences, one can conclude that magnetic forces dominate over the gravitational force and that the force-free approximation can be applied when considering the magnetic structure of active prominences. On the other hand, pressure gradients along the field lines drive plasma motions against gravity, so that the cold plasma is not confined only in the dips of the magnetic field lines as it should be in the case of hydrostatic equilibrium. However, down-
Fig.1. Quasistationary relaxation of one arc of the prominence observed on March 15, 1977. The parameter $X=\tan \theta$ is presented as a function of the prominence axis height ($h$) normalized with respect to the radius of the prominence cylinder. Circles represent measurements at the top and squares represent measurements in one leg of the prominence, respectively.

Fall of cold plasma along the field lines is sometimes governed by gravitation as is the case in post-flare loops (Vršnak, 1984).

3. Evolution Through a Series of Quasi-Equilibrium States

Apparently, prominences are close to the threshold for an eruptive instability onset when the pitch angle of helical threads becomes large ($X=\tan \theta \geq 1$). In such cases, as well as in the cases of very intricate internal structure, a prominence tends to simplify its configuration and to escape the onset conditions for kink-type instabilities by a nonviolent evolution which can be described as a series of quasistatic states (Figures 1, 2 and 3).
Fig. 2. Quasistationary relaxation of two elements in one arc of the prominence of March 15, 1977 (see Fig. 1). Evolution of the total twist $\Phi$ is presented as a function of the length ($L$) of the prominence normalized with respect to the diameter of the prominence's cylinder ($2r_0$). The line dividing stable and unstable regions for $\beta=0$ is drawn according to Hood and Priest (1979).

The prominence slowly risen and the pitch angle decreased due to the prominence stretching. In Figure 1 we show the phase of the quasistationary relaxation of one arc of the prominence of March 15, 1977, described by the parameters $X=\tan \theta$ and $H=h/r_0$, being the ratio of the height $h$ and the radius $r_0$ of the prominence. It seems that the total twist is preserved, as the change of the parameter $X$ is approximately proportional to the rate of stretching and radial expansion. In Figure 2 we show the comparison of the evolution of the twist ($\Phi=2\pi r_0/\lambda$) of the prominence with an estimate of an upper limit of the twist for $\beta=0$ based on the stability analysis by Hood and Priest (1979). In Figure 3 the quasistationary relaxation of another arc of the same prominence is shown.
Fig. 3. Quasistationary relaxation of another arc of the prominence of March 15, 1977: (a) the height \( h \) of the prominence as a function of time; (b) the parameter \( X = \tan \theta \) as a function of time.

4. Prominence Eruptions

During the quasistatic relaxation of the intricate magnetic structure, sometimes the critical conditions for the eruptive instability can be reached, depending on the initial magnetic configuration. Then, after a phase of slow rising motion (quasistatic evolution) an acceleration phase starts causing a fast upward rise of the prominence. The stored energy releases on an Alfvén time scale in the dynamical process of the flux tube eruption. In Figure 4 we describe measurements of the eruptive prominence observed on August 16, 1988, which was characterized by a small acceleration, a slow ascending velocity and a tendency to achieve an upper equilibrium position. Such a type of eruptions link the processes of relaxation through a series of quasi-equilibrium states with "violent eruptions" having a large and continuous acceleration up to the velocities sufficient to expel the prominence into the interplanetary space.

The evolution of an effective twist \( \Phi \)/\( D \) in the prominence \( (\Phi = 2\pi r_g/\lambda \) and \( D = d/r_0 \), where \( d \) is the footpoint half-separation) is shown in Figure 4. The circles represent the values measured in an element of the prominence at its

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Fig. 4. The evolution of an effective twist $\Phi/D$ in the eruptive prominence of August 16, 1988, as a function of the parameter $Z$ - the height of the prominence normalized with respect to the footpoint half-separation. Circles represent the measurements close to the summit of the prominence axis and the squares the measurements in one footpoint.

mit and the squares the values measured close to one footpoint of the prominence. The thin line represents an estimate of the border between stable (lower and left to the curve) and unstable region (upper and right from the curve) according to Vršnak (1990a). The phase of the acceleration occurred in the period when the "summit-element" values of the effective twist were in the "unstable region" of the graph. In Figure 5 we present the height $(h)$ and acceleration $(a)$ of the prominence during its eruption (the thick and thin line, respectively). The phase I corresponds to the slow rising motion $(v=1 \text{ km/s}, a=0 \text{ ms}^2)$ i.e. evolution through a series of quasi-equilibrium states. After the phase of acceleration characterized by an acceleration of $a_{\text{max}}=10 \text{ ms}^2$ (phase II) the constant velocity phase (III) sets in $(v_{\text{max}}=35 \text{ km/s})$. Late phases of the eruption were characterized by deceleration with a tendency to achieve an upper equilibrium position (phase IV).
7. Conclusions

A considerable fraction of prominences exposes a cylindrical-like geometry with a helicoidal-like internal structure (Vršnak, Ruždjak and Rompolt, 1991) revealing that the magnetic structures in the corona tend to be in the form of twisted magnetic configurations. In the first approximation, the magnetic field of helicoidal prominences can be described by an uniform twist configuration. In some cases, the transport of twist into the expanded part of the tube can be observed. The motions of the prominence plasma along the fine structure threads disclose the importance of pressure gradients along the field lines, implying that the hydrostatic approximation is not valid. The inferred magnetic field strength in the order of 20 G is sufficient to channel the mass motions. A value of $10^{11}$ A can be deduced for the axial electric current. When the twist of the field lines becomes large, the structure tends to relax through a series of quasi-equilibrium states. If the critical conditions for the eruptive instability are reached (Vršnak, Ruždjak and Rompolt, 1991) the prominence body is accelerated and erupts to an upper equilibrium state (Vršnak, 1990b). It seems that prominence dynamics...
occurs in a sequence from a "quasistatic evolution", over "weak eruptions" (only short and weak acceleration phase) up to "violent eruptions" (large, continuous acceleration).

References


DINAMIKA I STABILNOST HELIKOIDALNIH MAGNETSKIH USTROJSTAVA U SUNČEVOJ KORONI

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Sažetak. Izučavana je unutarna građa trideset prominencija helikoidalnog ustrojstva. Vlakna vidljiva u liniji Hα pokazuju da se magnetska polja koja prožimaju prominencije mogu opisati konfiguracijom jednolike usukanosti. Opisuje se prijenos usukanosti u prošireni dio magnetske cijevi jedne prominencije. Prominencije velike usukanosti uzdižu se i istežu prolazeći kroz niz kvazi-ravnotežnih stanja te na taj način izbjegavaju naglu relaksaciju ustrojstva magnetskog polja. Klasičan proces erupcije zbiva se ukoliko se tijekom takvog razvoja ostvare uvjeti za eruptivnu nestabilnost.