THE EJECTION OF HELICAL FIELD STRUCTURES THROUGH THE OUTER CORONA

LEWIS L. HOUSE
High Altitude Observatory, National Center for Atmospheric Research

AND

MITCHELL A. BERGER
Advanced Study Program and High Altitude Observatory, National Center for Atmospheric Research

ABSTRACT

The 1980 May 5 coronal mass ejection observed by the SMM coronagraph polarimeter contained an eruptive prominence with apparent helical structure. After a general discussion of the morphology of this event, we describe the evolution of the prominence structure as it traversed the outer corona. Particular attention is given to the distribution of magnetic helicity, a measure of helical structure. This distribution can be inferred by tracking the crossovers between individual filaments within the prominence. The northern leg of the prominence consisted of two braided Hα filaments shredded into subfilaments near the top. Much of the helicity in this leg resided in a compact central region. As the prominence rose, the central region unwound by expanding rapidly along the leg. This expansion could arise from both acceleration of the prominence material and spreading of the distribution of helicity along the leg.

Subject headings: Sun: corona — Sun: prominences

I. INTRODUCTION

Eruptive prominences in the outer corona (1.5–6.0 \( R_\odot \)) have been observed with the High Altitude Observatory's coronagraph polarimeter (C/P) onboard the Solar Maximum Mission satellite (SMM). These observations from the satellite are the first to isolate, through a narrow-bandpass Hα filter, the Hα emission from prominence material out to a distance of 6 \( R_\odot \) from the Sun's center. Portions of the ejected prominence material remain in the distant corona for many hours, indicating that even though much of the prominence leaves the near-surface region, the cool prominence material remains insulated from the hot outer corona. Prior to these observations the cool, Hα-emitting material could only be inferred to be present in broadband observations from other satellites (c.f. observations from ATM [Poland and Munro 1976] and from Solwind [Sheeley et al. 1981]). Of course, obvious correlations with eruptive prominences as observed from the ground and from other spacecraft suggested the presence of Hα-emitting material in the distant outer corona prior to the observations from SMM.

Several mass ejections containing Hα-emitting material are now under investigation, with each study proceeding from a slightly different point of view. In this paper we treat only the one event of 1980 May 5 and concentrate in particular on the evolution of helical structure within the prominence as it traverses the outer corona. An investigation of the radiation from prominences seen in the far corona has been initiated by Athay and Illing (1985). Additional work by Illing and Hundhausen (1985) treats prominence dynamics and Hα emission. Our study of the May 5 event is significantly enhanced by the addition of ground-based data from Wroclaw Observatory (Rompolt 1985), showing the quiescent prominence prior to, and during, its lift-off and passage through the lower corona.

Ground-based observations of prominences have frequently revealed apparent helical structure; recall the spectacular event of 1948 June 4 (Larmore 1953). Observations of mass motions also hint at such structure (Rompolt 1975). Furthermore, images of the 1980 May 5 coronal mass ejection (CME), as well as other events seen by C/P, strongly suggest the existence of helical structure. Some theoretical attempts have been made to discuss the problem of the helicity of eruptive prominences. The prominence considered in this paper was also considered by Pneuman (1984); a general treatment of twisted magnetic flux tubes is given in Parker (1979, Chap. 9). Pneuman's study emphasizes the factors affecting the wavelength and pitch angle of the twisted field lines. As the prominence stretches, the wavelength will increase because the same number of windings must be distributed over a greater length. This effect also decreases the pitch angle, unless the radius of the prominence increases faster than the length. A rising prominence encounters decreasing external gas pressures, which can lead to an expanding radius (unless the prominence cools as it rises). Parker suggests that, in general, twisted flux loops tend to concentrate their twist at the most expanded part of the loop, i.e., near the top. We will address this point in detail later. The axisymmetric twisted flux tube provides the simplest model of helical prominences. However, a truly axisymmetric tube varies only in the radial direction; such tubes cannot provide the observer with any indications of helical structure. In order to explain an observation of helical structure, we must go beyond the axisymmetric theory. One possibility is that only the thermodynamic parameters show significant helical structure. For example, inside an axisymmetric tube the plasma might condense along one or more field lines. The twisted field lines, and hence the density enhancements, trace out helical curves. If the magnetic field strength is much greater than the gas pressure, however, the field remains approximately axisymmetric.
A second possibility is that both the field and the plasma exhibit significant helical variation. In this case, a theoretical idealization based on helical symmetry rather than on axisymmetry may be more appropriate for modeling. In a helically symmetric configuration, quantities vary as, say, $f(r) \cos (m\theta + k_z)$, where $r$, $\theta$, and $z$ are cylindrical coordinates, $m$ gives the number of "filaments,” and $2\pi/k$ gives the wavelength of the helices. Helically symmetric configurations may arise, for example, when a flux tube has been given a large amount of twist. In this situation axisymmetric equilibria can be kink unstable, leaving helically symmetric states as the only (known) possibility for equilibrium. Helical equilibria are discussed in general terms by Tsinganos (1982). Little work has been done in applying them to coronal structures, and their behavior may be quite different from axisymmetric equilibria. Observations of the distribution of helicity of a prominence may help in constraining both axisymmetric and helically symmetric prominence models. Furthermore, the increase in wavelength of the helical structure as the prominence travels several solar radii may be important to the overall dynamics of the prominence.

The main purpose of the paper, therefore, is to study the evolution of the helical structure and to describe and investigate the kinematics of the prominence. As strictly a secondary aspect, we also briefly describe the coronal transient that occurs in association with the prominence ejection. The organization of the paper is as follows: First, in § II we present a general discussion of the various methods of describing and quantifying topological structure. Next, in § III, we describe the morphological and kinematic behavior of the prominence, utilizing both ground-based and spacecraft-based observations. As part of this treatment we also consider the CME. In § IV we discuss possible interpretations of the observed helical structure. Conclusions are presented in § V.

II. THE GEOMETRY OF HELICAL FIELDS

The field line geometry of an axisymmetric flux tube can be described quite simply; one specifies the pitch angle $\lambda$ of a field line as a function of radius. Alternatively, the twist angle per unit length $d\theta/dz$ might be given [$d\theta/dz = (1/r) \tan \lambda$]. For helically symmetric or asymmetric fields, however, the geometric description becomes both richer and more difficult. Local quantities such as $\lambda$ and $d\theta/dz$ lose their significance because the field lines do not fit neatly into a cylindrical coordinate description. Also, global averages of such quantities must be chosen carefully if they are to have a useful geometrical meaning. Nevertheless, a few well-defined quantities describing general helical configurations could be useful in the interpretation of both observations and theoretical models.

The magnetic helicity integral (Woltjer 1958; Moffatt 1969; Berger and Field 1984) provides the most basic measure of helical structure in a magnetic field. Because the helicity integral relates to diverse field structures and obeys simple evolution and conservation laws, it may provide a unifying concept in the study of field morphology. Braided prominence filaments provide one example of a configuration possessing helicity; others include sheared arcades, flux tubes with twisted field lines, kinked tubes, and emerging flux regions (where the emerging flux is oriented obliquely to the old flux). For force-free fields ($B = aB_0$), if one separates the field into subregions where $a$ is all of one sign, then each subregion will have a helicity content. Inside volumes bounded by a magnetic surface (i.e., no field lines cross the boundary), the helicity integral is conserved by ideal magnetohydrodynamic motion (Woltjer 1958). Field lines do pierce the boundary of the corona (e.g., the photosphere); in this case helicity is conserved by ideal motions which vanish at the boundary (Berger and Field 1984). Changes in helicity can arise from rotations of individual photospheric footpoints, or angular motions of footpoints about each other.

The basic structure suggested by the SMM images analyzed in § III consists of two filaments braided about each other. We suppose that the filaments are surrounded by essentially distinct magnetic flux tubes. The magnetic helicity of such a configuration arises from the braiding between the tubes, the kinking of each tube, and the twist of field lines within the tubes (Berger and Field 1984). First consider the braiding. If each filament were a closed ring, then the net amount of braiding could be described by the linking number $L_{12}$ of the two filaments, i.e., the number of times one filament encircles the other. The corresponding helicity contribution is $H = 2L_{12}$ $\Phi_1 \Phi_2$, where $\Phi_1$ and $\Phi_2$ denote the magnetic fluxes of the filament tubes. In close analogy, the helical structure of a DNA molecule is also measured by computing a linking number between the two nucleotide chains (Fuller 1971; Crick 1976).

As seen in projection, two filament rings exhibit crossovers; the linking number then equals half the number of right-handed minus left-handed crossovers. If the filaments do not close upon themselves, then a generalized linking number can still be defined (Fuller 1978; Berger 1986). For example, for two curves stretched between two parallel planes, the linking number equals the angle through which the curves rotate about each other while traveling from bottom to top planes (divided by $2\pi$). We can still roughly approximate this number by counting the crossovers seen in projection. This technique will be used in the next section for analyzing the prominence images.

Next consider the structure of an individual filament (or magnetic flux tube surrounding a filament). The helicity of a filament arises from the twist of internal field lines about the filament axis and from the winding of the filament axis about the prominence (Berger and Field 1984). The mathematical description of helical flux tubes derives from the study of supercoiled DNA molecules. The two nucleotide chains twist about the axis of the DNA molecule, but the axis is itself highly coiled, in order to fit the molecule into a compact volume. Both of these structural features can be quantified (Fuller 1971): the "twist number" $T_\theta$ measures the twist about the axis and the "writhing number" $W_\Theta$ measures the twist of the axis itself (for calculational details, see Fuller 1971; Crick 1976; Berger and Field 1984). The sum of these two quantities equals the linking number of the chains. The relative amounts of twist number and writhing number for a DNA molecule have important biological implications (for a nontechnical review, see Bauer, Crick, and White 1980). Similarly, these quantities may be important to the dynamics of helicity-carrying magnetic flux tubes.

For example, up to a certain amount of helicity per unit length (depending on boundary conditions) an axisymmetric flux tube ($W_\Theta = 0$) provides the stable configuration. For larger values of helicity, the axisymmetric solution becomes unstable to helically symmetric kink modes, which transfer some of the helicity into writhing number. In particular, the Krasilnik-Shafranov limit predicts instability when the twist is equivalent to about one complete turn (Voslaumber and Callebaut 1962; Zweibel and Boozer 1985). The effects of photospheric line...
tying may increase this value; for example, a uniformly twisted force-free tube goes unstable at a twist of about $3.3\pi$ (Hood and Priest 1979). By increasing $W_r$, one decreases the azimuthal field strength at the expense of lengthening the tube. These effects, as well as the influence of the external medium confining the tube, help determine the minimum energy distribution of $T_e$ and $W_r$ for a given helicity.

Berger (1984) and Boozer (1986) have found severe constraints on helicity dissipation $dH/dt$ in resistive plasmas; in particular, a Schwarz inequality relates the helicity decay to the energy $E$ and energy decay $dH/dt$:

$$\left(\frac{dH}{dt}\right)^2 \leq 128\pi^2 \tilde{\eta} E \frac{dE}{dt},$$

where $\tilde{\eta}$ is the mean resistive diffusion coefficient (weighted by $B^2$). For example, an isolated uniformly twisted tube of radius $R$ and temperature $T$ cannot lose its helicity on a time scale less than $\sim 3 \times 10^{13} (\tilde{\eta})^{-1} R^3 T_6^{1/2}$ s, where $\eta$ is the classical Spitzer resistivity, $R_g = R/10^6$ cm, and $T_6 = T/10^6$ K. Thus, rapid reconnection may alter the topology of a field but probably not its helicity. If, for example, a sheared arcade reconnects to form a prominence, the helicity inherent in the shear may provide the source of twist or braiding for the prominence (e.g., see Pneuman 1983).

III. OBSERVATIONS

The eruptive prominence in this study was observed by the C/P on the SMM satellite on 1980 May 5. A CME occurred in association with the eruption of the prominence. The first indication of the event as observed from the spacecraft was the appearance of a loop or shell of bright coronal material recorded at 10:41 UT at 24° N. The prominence was observed prior to lift-off and through the initial stages of the ejection through the lower corona by the ground-based observatory at Wroclaw, Poland. The first indication of lift-off from the ground-based observations was at 10:02 UT at P.A. = 289°. We shall now give more details that describe the ground-based observations, and we shall follow this with a description of the spacecraft-based observations.

a) Ground-based Observations

Figure 1 (Plate 9) shows a sequence of images beginning at 07:21 UT and ending at 10:35 UT. Some evidence of helical structure can be seen in these images. The central third of the prominence is too convoluted to make definite statements about its structure, but at the sides of this central part there are suggestions of helical winding. Note that the northern leg of the prominence (left side of each image) consists of two filaments rooted ~7° apart at the surface. The two filaments become tangled together soon after leaving the surface. The southernmost leg of the prominence seems to be released in the time frame 9:27–10:02 UT while the northern leg remains fixed, thus giving the ejection of the prominence a whiplike motion. This is not an uncommon behavior as seen from ground-based observatories. The relationship of this motion to that of the CME will be discussed further below.

Inferences from synoptic maps suggest that the prominence is aligned north-south and centered at ~22° N with a length of ~1.8 x 10^5 km (Rompolt 1985). Because of the north-south alignment, projection effects should not be important in the morphological study of the prominence.

Spacecraft-based Observations

A sequence of images taken by the C/P is shown in Figures 2, 3, and 4 (Plates 10, 11, and 12, respectively). Noted on each image of the composite is the time as well as the filter used, either the broad-band green filter (GREEN) or the Hα filter. The Hα data were taken through a 40 Å (FWHM) filter with an exposure of 3 minutes. The leakage of the continuum through the filter permits one to clearly see both the coronal material of the transient and the cool Hα prominence material. The broad-band green filter is 350 Å (FWHM) centered at 5171 Å, and the corresponding exposure time for these images is about 8 s. The transmission of this filter at the wavelength of Hα is ~10^{-5}; hence, it effectively excludes Hα radiation.

Each coronagraph image is ~6 R⊙ on a side, and the dark edge of the occulting disk shadow is at 1.5 R⊙. The north-south axis of the Sun is aligned from the upper left-hand corner (north) to the lower right-hand corner. In all succeeding images, the same orientation and scale are maintained. We next describe the associated transient before proceeding with the discussion of the Hα features.

i) Transient

The early stages of the transient as observed in the coronagraph field of view are clearly visible in Figure 2. Figure 2a shows the corona prior to the event.

Some aspects of the timing of the event may be noted. First, the time from the initial disruption of the prominence at 10:02 UT until the leading edge of the prominence is just visible at the occulting disk is 45 minutes, indicating an average velocity of ~130 km s⁻¹. This is intermediate in the range of velocities measured from the ground-based coronagraph. The first three images of the bright front in Figure 2 are too close temporally to give an accurate velocity measurement. However, it has been possible to bring out this feature in an additional image utilizing image enhancement techniques.

With some difficulty, the transient can be seen near the outer edge of the field of view, in Figure 3a. This figure was enhanced by differencing the exposure at 11:38 UT with an image of the corona prior to the event at 9:59 UT and then significantly increasing the level of contrast. With this additional image, it is possible to obtain a measurement of the transient velocity projected against the plane of the sky. It is found to be 650 km s⁻¹.

The images suggest that the transient significantly altered the global structure of the surrounding corona, as is observed in many other CMEs. This can be seen most clearly beginning with the image in Figure 3a. Comparison of this image with Figure 2a shows the extent to which the transient disrupted the preexisting corona. The streamers seen over the equator are highly distorted and have moved well outside of the bright looplike feature. There also exists a peculiar dark channel between the transient and the streamer at the southern edge of the transient. In addition, we note that there is a significant amount of structure apparently entrained within the transient, as can be seen in Figures 3a and 3b. This region is highly structured and has the form of a multitude of loops. Perhaps two contributions to this region exist, one clearly the Hα prominence material and the other a more diffuse component of loop structures seen in white light (possibly a part of the preexisting magnetic configuration). The dark southern boundary could be a region of compressed magnetic field, void of material. The presence of this region seems to distort the nearby streamer.
Fig. 1.—Eruptive prominence of 1980 May 5 as observed from Wroclaw, Poland (courtesy B. Rompolt)
Fig. 2.—Coronagraph/polarimeter images. The north-south rotation axis of the Sun runs from upper left-hand corner of each image to lower right-hand corner. Field of view is $\sim 6 \times 6 R_\odot$. Occulting disk is at $1.5 R_\odot$. Date and filter designation are indicated. (a) Prior to event; (b) mass ejection on west limb; (c) mass ejection; (d) mass ejection with prominence material overexposed at edge of disk.

House and Berger (see 323, 408)
Fig. 3.—Coronagraph/polarimeter images (a) image enhanced to leading edge of mass ejection and prominence structure; (b) fine wispy prominence material; (c) and (d) prominence in Hα showing helical structure.

House and Berger (see 323, 408)
Fig. 4.—Coronagraph/polarimeter images: (a)-(d) ejected prominence unwinding through outer corona

House and Berger (see 323, 408)
EJECTION OF HELICAL FIELD STRUCTURES

The eight images in Figures 3 and 4 and the drawings in Figure 5 display the evolution of the helical structure during the ejection of the prominence magnetic field. In this sequence, from 11:38-12:24 UT, the northern leg of the prominence is most visible. It is in the northern leg that the apparent unwinding occurs. This leg appears to be made of at least two filaments exhibiting several crossovers. For the purposes of this section, we will assume that the crossovers are a result of braiding between the filaments. This assumption will be discussed in more detail in the next section.

We are interested in the wavelength of the braiding, i.e., the distance between successive crossover points. The evolution of this length is most evident in the Hz images at 11:53, 12:05, and 12:16 UT. At 11:53 UT the prominence appears tightly wound. In the lower portion of the prominence, the period of the braiding is approximately 0.4 R⊙, whereas near the upper visible portions of the prominence, the period is approximately 0.15 R⊙. As the prominence moves outward, at 12:05 and 12:16 UT, one sees a general decrease in pitch angle and an increase in wavelength of the braiding. The images in the broad-band filter confirm these general statements; plus they show that at the greatest heights bright subfilaments seem to be branching from, or "peeling off" the main filaments as the prominence rises through the corona (see Fig. 3). In contrast, the vertical or radial portion of the prominence appears to be tightly constrained.

The two filaments in the SMM images may correspond to the two filaments seen in the northern leg of the ground-based pictures (Fig. 1). The distance between the filament footpoints is about 8 x 10⁴ km. During a time scale of a few hours, these footpoints can change their relative orientation by at most a few degrees (given photospheric speeds of 1 km s⁻¹). Thus, the total angle through which the filaments are braided should change little during the course of the ejection. We should point out that some braiding structure may not be visible because of the occulting disk shadow. If such structure were to rise into the visible part of the corona, the net braiding angle could change. If this occurred, it would be difficult to detect because the images are not clear near the disk shadow. Of course, the net braiding could also change due to reconnection between the filaments, but there is no clear evidence for this phenomenon in the images.

The interpretive drawing in Figure 5 attempts to illustrate the salient features of the images that are difficult to see in the reproductions. These drawings have been made by (subjectively) picking out the features which most clearly suggest linear structure. Such features include elongated, cigar-shaped blobs, or a succession of such blobs, whose edges appear aligned. In some circumstances, the linear patterns join bright features to relatively faint structures. Thus, simple image processing techniques, for example, filtering out high- or low-intensity signals, are of limited use in tracing the filamentary structure. The Hz images show the most structure, but because of the complexity of this structure the topology of the filaments becomes more ambiguous. On the other hand, in the white-light images, which show less detail but are easier to trace, some of the topological structure may remain undetected. For example, the Hz image at 11:53 UT (Figure 3c) shows at least two crossovers in the tight central segment of the prominence leg, but the white-light images smear these crossovers into one. The four points labeled A, B, C, and D will be explained below.

The first few images are faint and somewhat difficult to interpret, but the 11:45 and 11:51 UT images seem to display four crossovers. Some of the filamentary structure at the top is shown for 11:38 and 11:51 UT. The next drawing is an interpretation of the Hz image at 11:53 (Fig. 3c). Five crossovers can be inferred; we caution, however, that the structure above the third crossover is somewhat ambiguous because the filaments are nearly parallel there. In the next four drawings, to 12:03 UT, three crossovers are seen. The middle one, which probably corresponds to the middle crossover (or crossovers) in the earlier drawings, seems to elongate into a segment. It may be that additional structure is hidden in this segment (e.g., consider the Hz images at 11:53 and 12:05 UT). Because of the difficulty in interpreting the data, there can be no firm conclusions as to whether or not the actual number of crossovers within the field of view stays constant.

Figure 6 summarizes the observed motions of the crossovers. Time-height diagrams are shown for the four points on the north leg labeled in Figure 5. Point D represents the bottom of the uppermost crossover. This point can be tracked from 11:38 to 12:13 UT, after which it disappears from view. Points A and C locate the lower and upper boundaries of the central segment. At 11:45 UT and after, A can be determined by the point at which the two filaments begin their second crossover; before this time, A is inferred to be the lower tip of the central blob. Point C cannot be determined before 11:57 UT. Point B tracks a bright spot at the center of the second crossover; the distance between points A and B stays roughly constant during the ejection.

The top crossover D has a radial velocity component of 446 ± 24 km s⁻¹. Also, this crossover moves to the right (south), in contrast to the motion of the rest of the prominence. The high speed may in part reflect a scissor effect: the prominence as a whole rolls to the left in order to become more and more radial. If the top filament executes this motion faster than the bottom filament, then the crossover could have a net southerly motion. The diagrams also show that the central segment expands rapidly, as the top (C) moves at 264 ± 21 km s⁻¹, whereas the bottom (A) moves at only 119 ± 13 km s⁻¹. Unfortunately, there are too few data points to determine the respective speeds of the top and bottom at the same radius but different times. The crossover velocities are comparable to the Alfvén velocity: Athay and Illing (1985), in a study of similar erupting prominences observed by SMM, find average densities of 10⁸ cm⁻³ and suggest that the field strength should be near 1 G. With these values, the Alfvén velocity is about 200 km s⁻¹, with a large uncertainty due to poor knowledge of the field strength.

IV. DISCUSSION

First, we will discuss whether crossovers between filaments can be reliably employed as an indication of braiding. If two filaments are truly braided, then one filament will successively cross over, and then under, the other filament (see Fig. 7a). Unfortunately, the coronagraph does not enable us to tell which filament is "on top" at a given crossover. Thus, for example, the possible configuration sketched in Figure 7b, which has zero helicity, will look the same as the truly braided configuration in Figure 7a. There are several arguments, however, which suggest that the situation described by Figure 7b is unlikely. First, the configuration in Figure 7b will only exhibit crossovers from certain viewing angles, whereas that in Figure 7a will have the same number of crossovers independent of viewing angle. Also, the lateral proximity and vertical
alignment of the two filaments in Figure 7a (as seen in projection) is purely fortuitous, whereas in Figure 7a the braiding ensures that the filaments will be closely aligned. Second, as the prominence moves through the corona, the two filaments in Figure 7b may well move laterally apart, making pairs of crossovers approach each other and then disappear. We have seen no evidence for this behavior. Third, whereas helically symmetric equilibria similar to those in Figure 7a are known to exist (Tsinganos 1982), structures like those in Figure 7b seem quite unstable. For these reasons we assume in this paper that the prominence displays true braiding. Of course, there could be additional helical structure within each filament, which would not be observed, but which could affect the prominence dynamics.

Assuming that the crossovers observed are real, we may estimate a lower limit to the helicity of the prominence. In the visible northern leg, the $H\alpha$ images show four to five crossovers, whereas the broad-band images typically display 3 crossovers. One might interpret differences in crossover numbers between images as a consequence of inadequate resolution, rather than as an actual change in the topology of the visible leg. On the other hand, if helical structure flows into or out of the visible portion, the number of visible crossovers might truly change. The helicity of the total prominence, however, would remain constant. Furthermore, reconnection between filaments could conceivably remove a crossover. In this case helicity will be conserved during the reconnection (Berger 1984) unless there exists several orders of magnitude of anomalous resistivity over the entire prominence. Additional twists or kinks within individual filaments would then store the helicity of the crossover. Unfortunately, the observations do not have the resolution to test helicity conservation.

In conclusion, the large-scale braiding in the northern leg alone displays at least three to four crossovers, or one and one-half to two complete turns. Additional helicity may be present in the unseen parts of the prominence, or in small-scale structure within the northern leg (the additional structure seen in the $H\alpha$ images supports the latter possibility). If the field...
were approximately axisymmetric two turns (say) would correspond to a magnetic helicity of \( H = 2\Phi^2 \), where \( \Phi \) is the net magnetic flux of the prominence. For more complicated fields, this relation is not precise; e.g., the twist and writhing numbers (see § II) of the filaments could differ from the values for filaments within an axisymmetric field. However for the present purposes, a rough estimation based on the number of crossovers will suffice.

Is the prominence studied in this paper better described by an axisymmetric state or a helically symmetric state? As mentioned in the introduction, the apparent helical structures in images of the prominence can arise either from density inhomogeneities superposed upon an otherwise axisymmetrically twisted configuration or from actual helical structure in the field. Given our estimated lower limit of \( H \geq 1.5-2\Phi^2 \), it is probable that the original quiescent prominence was beyond both the Kruskal-Shafranov limit and the Hood-Priest limit for axisymmetric stability (see § II). These limits do not describe all possible axisymmetric configurations; nevertheless, the strong possibility exists that the prominence was in a helically symmetric state.

Helically symmetric flux tubes may display different behavior from axisymmetrically twisted tubes. For example, the external atmospheric pressure gradient will not be able to hold up a dense helical filament. Thus, for a vertical flux tube, the coils will tend to collect in the lower regions. This implies a decrease of pitch angle with height, which results in a vertical magnetic curvature force. If this curvature force alone balances the gravitational force perpendicular to the filament, then it is simple to show that \( \lambda = \lambda_0 e^{-gV_A^2} \), where \( \lambda \) is the wavelength of the coiling, \( g \) is the gravitational acceleration, and \( V_A \) is the Alfvén velocity. Note also that the response times for a helical field may be different than those for an axisymmetric field. For example, a small amplitude kink wave on a thin straight flux tube will move slightly slower than the Alfvén speed within the tube because it must plow through the outside medium (Spruit 1982).

If a tube has a nonequilibrium helicity distribution, then the unbalanced Lorentz forces can lead to violent behavior (Shibata and Uchida 1985). For example, if the helicity is
clumped in one section, the a rapid expansion of the helical structure along the length of the tube will result. Unbalanced helicity distributions within a tube can be created, say, by reconnection with a second tube or, with more relevance to our purposes, by the sudden release of one leg of the tube. The large-scale motions generated by the relaxation of unbalanced helicity distributions have been studied by Shibata and Uchida (1985).

Suppose we assume that the filaments form the visible dense cores of topologically distinct magnetic flux tubes. In the early stages of the prominence eruption, the filaments are tightly wound about each other, implying that such flux tubes have radii not much greater than the radii of the Hα-emitting filaments (unless the radius of a filament is below resolution). At later stages, the situation is rather complex. Near the bottom of the tube the filaments are relatively far apart, but there is a central region where they are still tightly wound, and in the upper part subfilaments seem to break off and diverge. The structure of the upper and lower thirds is consistent with a substantial expansion of the medium surrounding the filaments, but the middle third is anomalous.

The time-height diagrams of Figure 6 show some evidence of the crossover pattern moving with respect to the global expansion of the prominence. In particular, the upper crossover moves in a transverse direction contrary to the prominence as a whole (which rolls upward to become more and more radial). This suggest a scissor effect. Most interesting is the evolution of the central tightly wound region. The Hα images (Figs. 3 and 4) show substantial braiding within this region. The top travels upward twice as fast as the bottom, indicating that the central region rapidly expands as the prominence rises. Two mechanisms can contribute to this effect. First, if the mass ejection as a whole accelerates in situ in the outer corona, then matter will travel faster at higher radii than at lower radii. Thus any pattern associated with the prominence will expand in the radial direction. Second, at the boundaries of the tightly wound segment there is a gradient in pitch angle which, as mentioned above, creates a strong Lorentz force. This force should drive a local expansion of this part of the prominence, perhaps even contributing to the overall prominence motion. Both these mechanisms involve a stretching of the prominence material due to acceleration. The first mechanism treats the prominence helicity as a passive feature: external forces drive the acceleration. The second mechanism, on the other hand, treats the prominence helicity as an active participant in the dynamics of the expansion.

Recall Parker's (1979) assertion that twist should reside at the top of a coronal configuration. The initial prominence structure seems to exhibit this behavior, but, in the erupting phase most of the helicity seems to be contained in the northern leg. The ground-based observations suggest that the initial whip like motion lifted and tilted the top of the quiescent prominence, converting it into the northern leg seen in the SMM images. The new, highly twisted northern leg probably did not have an equilibrium distribution of helicity. The rapid expansion of the central segment perhaps reflects an attempt at readjustment of the helicity distribution. Of course, the readjustment may not have been able to proceed much faster than the general expansion of the prominence.

IV. CONCLUSIONS

The observation of an eruptive prominence, following it from prior to lift-off to its passage through the outer corona, has permitted a view of helicity on a grand scale in nature. The ground-based observations, although they cannot be interpreted completely unambiguously, show a tightly twisted prominence at the limb of the Sun on 1980 May 5. During the subsequent 3 hr covered by the SMM coronagraph/polarimeter the evolution of the magnetic field structure of the prominence appears to have behaved in the fashion of an expanding helix.

Magnetic helicity considerations can help in the study of the origin, morphology, and development of prominences. Helicity provides a unified measure of the topological aspects of field structure; also, it is expected to be conserved to an excellent approximation in the corona. Thus the helicity inherent in a sheared arcade can be transformed, through reconnection, into the helicity of a twisted prominence. The prominence morphology depends on the amount of helicity present. Prominences with large amounts of helicity do not have stable axisymmetric equilibria; helically symmetric equilibria may provide the only possible quiescent state. The 1980 May 5 prominence was quite possibly above the threshold for helical symmetry.

In general, the stability of a magnetic field may be correlated with its helicity; furthermore, if an instability does develop, the redistribution of helical structure can release a significant amount of free energy. The time development of helicity in the prominence under study is of special interest. In the ground-based limb measurements, the helicity appeared to be concentrated at the top of the prominence, as predicted by Parker. The initial eruption of the prominence consisted of whiplike motion, during which the top of the prominence pivoted upward and northward toward alignment with the northern leg. This action created a nonuniform helicity distribution within a vertical structure, which may have contributed to the acceleration and expansion of the prominence.

Helicity manifests itself in many realms of nature beyond that of the solar prominence: for example, in DNA structure (Crick 1976; Bauer, Crick, and White 1980), polymer structure in general (e.g., Bretron and Williams 1985), and astrophysical phenomena such as twisted flux ropes in the Venus ionosphere (Russell and Elphic 1979), helical galactic jets (Konigl and Choudhuri 1985), the recently discovered braided double galactic jet (Owen et al. 1985), and perhaps the field structure of supernova remnants (Rees and Gunn 1974). Because of similarities in structure and the relative advantages of solar observations, further study of prominence helicity may contribute to the understanding of these other astrophysical phenomena.

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MITCHELL A. BERGER: Applied Mathematics, University of St. Andrews, Fife KY16 9SS, Scotland
LEWIS L. HOUSE: National Center for Atmospheric Research, Boulder, CO 80307-3000

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