The Astrophysical Journal, 689: L73–L76, 2008 December 10

PERSISTENT HORIZONTAL FLOWS AND MAGNETIC SUPPORT OF VERTICAL THREADS IN A QUIESCENT PROMINENCE

Jongchul Chae, Kwangsoo Ahn, and Eun-Kyung Lim
Astronomy Program, Department of Physics and Astronomy, Seoul National University, Seoul 151-747, Korea
G. S. Choe
Department of Astronomy and Space Science, Kyung Hee University, Yongin 446-701, Korea
and
Takashi Sakurai
National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan
Received 2008 September 8; accepted 2008 October 20; published 2008 November 5

ABSTRACT

There has been some controversy as to whether the magnetic fields of vertical threads seen in quiescent prominences are predominantly vertical or horizontal. We report finding special patterns of flow in a quiescent prominence observed by the Solar Optical Telescope aboard *Hinode*. This prominence is a small hedgerow prominence composed of many vertical threads. To one side of it, we found a pattern of persistent horizontal flows of Hα-emitting plasma. These flows originated from a region in the chromosphere, rose to coronal heights, and then extended horizontally for a long distance until they reached the main body of the prominence. In the higher altitudes the flows either moved across vertical threads or lifted them up, while in the lower altitudes they often formed bright blobs of plasma and shed them, resulting in a sudden change of flow direction from horizontal to vertical. The observed persistent horizontal flows support a configuration of initially horizontal magnetic fields, and our results appear to be consistent with the traditional theory that vertical threads in quiescent prominences are stacks of plasma supported against gravity by the sagging of initially horizontal magnetic field lines.

Subject headings: MHD — Sun: atmospheric motions — Sun: magnetic fields — Sun: prominences
Online material: mpeg animation

1. INTRODUCTION

The existence of vertical threads and downflows in quiescent prominences has been known to solar observers (Engvold 1976; Zirker et al. 1994; Berger et al. 2008) for a long time, but their physical nature is not fully understood as yet.

One line of thought is to suppose that the magnetic field is predominantly vertical, and each thread represents a vertical magnetic flux tube (Malville 1976; Engvold 1998). This is based on the belief that thin and elongated plasma structures outline magnetic field lines. The threads seen in limb prominences are usually thin and vertically oriented. The descending motion seen in these threads appears to be consistent with this picture of vertically oriented magnetic field. The velocities of the descending motion, however, are much lower than free-fall velocities, and this raises the question of how plasma in a vertical flux tube can be supported against gravity (Engvold 1998). Different explanations have been proposed to solve this paradox of the vertical magnetic threads, including dynamical support by waves (Jensen 1990), an integrated effect of very thin fibers with free-falling material (Engvold 1998), and the dynamics of a density enhancement in a stratified atmosphere with a strong vertical field (Mackay & Galsgaard 2001).

Another set of models is based on the supposition that the magnetic field is predominantly horizontal, as has been inferred by a series of polarization measurements (e.g., Leroy 1978, 1989). The problem is then how essentially vertical fine structures of cool plasma can appear in a basically horizontal magnetic field (Zirker 1989; Tandberg-Hanssen 1995). Low (1982) constructed a magnetohydrostatic model made up of an array of vertical threads, hung in sagging magnetic field lines. It is an extension of the classical model of Kippenhahn & Schlüter (1957) for a single vertical plasma sheet of infinite extent. A more generalized solution was recently presented by Low & Petrie (2005) that takes into account not only the variation of the parameters from sheet to sheet, but also arbitrary constant uniform velocities relative to each other. Heinzel & Anzer (2001) also constructed a two-dimensional model of individual threads by generalizing the Kippenhahn-Schlüter model, focusing on the spectral characteristics of lines emitted by such a structure. In these models, the width of a thread is equal to the pressure scale height multiplied by a factor that is determined by the sag angle, which in turn depends on the amount of loaded mass. If no mass is loaded, the sag angle is close to zero, implying a horizontal field. The vertical threads are identified with vertically oriented current sheets that result from the local distortion of initially uniform horizontal magnetic field by gravity.

What kind of observational efforts can we make to resolve the controversy over the magnetic nature of the vertical threads in quiescent prominences? The best way would be to precisely determine the vector magnetic field in the threads. As a matter of fact, there have been such efforts (e.g., Leroy et al. 1983; Leroy 1989), but recent studies (Casini et al. 2003; Merenda et al. 2006) yielded inconsistent results for the direction of magnetic field.

An alternative approach is to examine the characteristics of flows in quiescent prominences in detail. Some information about the magnetic structure can be indirectly inferred from the observed characteristics of flows, since the velocity field is coupled to the magnetic field through the equations of motion and magnetic induction. For example, in the case of a strong magnetic field, flows may tend to be directed along the magnetic field lines, that is, field-aligned, changing the magnetic field little (see Zirker et al. 1998 for instance). However, inferring the magnetic field direction from flows should be done with great care, since flows are not always necessarily along magnetic field lines.

The Solar Optical Telescope (SOT; Tsuneta et al. 2008) aboard the recent solar mission satellite *Hinode* (Kosugi et al. 2007) has produced stable sequences of prominence images with subarcsecond resolution that are quite suitable for the study of internal flows in prominences. In this Letter we report finding persistent horizontal flows in a quiescent prominence observed by the SOT, which may shed light on the problem of supporting plasma against gravity in the vertical threads that make up quiescent prominences.

2. DATA AND ANALYSIS

We analyzed a set of Hα images of a quiescent prominence taken by the SOT on 2007 August 17. The prominence was observed for many hours at a cadence of 25 s. The pixel size of Hα images was 0.16″, and the field of view was 163″ by 163″.

The data were corrected for the dark and bias values, and cosmic ray hits were replaced by the medians of their neighbors. The Hα images showed a nonuniform response pattern, reflecting the defect of the narrowband filter, that is, bubbles inside the filter oil (K. Ichimoto 2007, private communication). Since this troublesome pattern varies randomly with time, we have no way to correct for it. As we shall see, however, our results are not sensitive to this pattern.

Images were aligned using the solar limb as the reference. We selected a number of points on the limb using a technique of edge detection, and fitted their positions by a circle. The standard deviation of the statistical error of determination using this method is estimated to be about 0.4 pixel (0.06″). Since we use the running median values for the alignment of images, the statistical error of the alignment may be smaller than 0.4 pixel.

The set of aligned images was analyzed in several ways. First, they were used to construct movies from which we could identify major temporal variations. Second, the velocity vectors on the plane of sky were determined at a number of spatial points from a pair of successive images, using the optical flow technique called nonlinear affine velocity estimator (NAVE, Chae & Sakurai 2008). Finally, we tracked features of interest for as long a time period as possible, by successively applying the NAVE to a sequence of images. The outcome is a trajectory of the features, from which the time variation of velocity and acceleration can be inferred.

It should be kept in mind that in general, optical flows do not necessarily correspond to plasma flows, irrespective of the specific method used. This is because what is seen in images represents the superposition of features along the line of sight, and because the apparent displacement of features could also arise from nonuniform changes in brightness. In the present study, we are mostly interested in the region where the line-of-sight overlapping is not serious, so we think that the optical flows may serve as a good proxy for the transverse motions on the plane of sky.

3. RESULTS

Our prominence of interest is a small, faint hedgerow prominence that was located outside the northwest limb of the solar disk on the observing day. Our examination of the full-disk Hα images taken at Big Bear Solar Observatory on the previous days revealed that the prominence was inconspicuous in Hα when it stayed on the disk, suggesting that its optical thickness at Hα was small. The movie accompanying Figure 1 in the online version of this article shows the sequence of all the Hα images taken during a period from 16:21 to 18:47 UT. It has a field of view 8.1×10^4 by 5.2×10^4 km, covering only a part of the prominence (see also Fig. 1). It consists of a number of vertical threads. The width of the thinnest thread was found to be about 0.6″. Along these threads, a number of plasma blobs formed and descended.

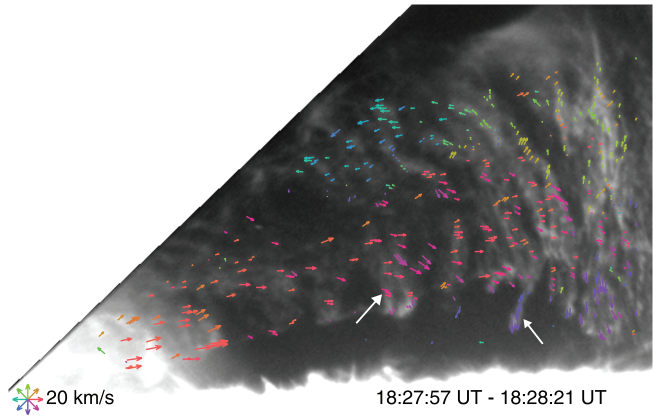

FIG. 1.—Velocity vectors superposed on a snapshot image. The white arrows near the center and on the right point to one of column-like structures newly made, and one of plasma blobs descending from horizontally moving column-like structures. See also the accompanying mpeg animation in the online *Journal*.

A comparison of the first and last images in the movie reveals a couple of characteristics suggesting that some vertical threads may have been newly made during the time interval between the two instants, or were still under formation/development up to the last instant. First, the volume occupied by vertical threads in the right half of the field of view got more extended both horizontally and vertically. Moreover, we find near the center of the images the emergence of new column-like structures of plasma that were more or less elongated vertically (see Fig. 1). These structures are not as thin and well-defined as, but look similar to, the vertical threads, probably representing the early stage of thread formation. These column-like structures were moving toward the right, while the vertical threads did not move much horizontally.

The movie clearly shows a persistent pattern of horizontal flows that can be easily identified from the displacements of a number of Hα emission patches. Even though the lifetime of each Hα emission patch was short, of the order of a few minutes, the pattern of flows inferred from the patches persisted for a much longer time. The flows started from a chromospheric region at the lower left corner of the images. They obliquely rose to coronal heights ($>10^4$ km), and then moved horizontally for a long distance up to 5×10^4 km at speeds of 10–30 km s^{-1}. This pattern is also clear from the velocity field at an instant as shown in Figure 1.

A careful examination of the velocity field in Figure 1 reveals that the horizontal flows are eventually bifurcated. At lower altitudes the flows shed dense Hα-emitting material downward, while at higher altitudes they move farther across the vertical threads without shedding material. These flows at higher altitudes seem to be responsible for the dynamic patterns such as the counterclockwise vortex motion seen in the upper middle region of the image and the lift-up of material seen in the upper portions of the vertical threads on the right. The mass and momentum transferred by the flows may have contributed to

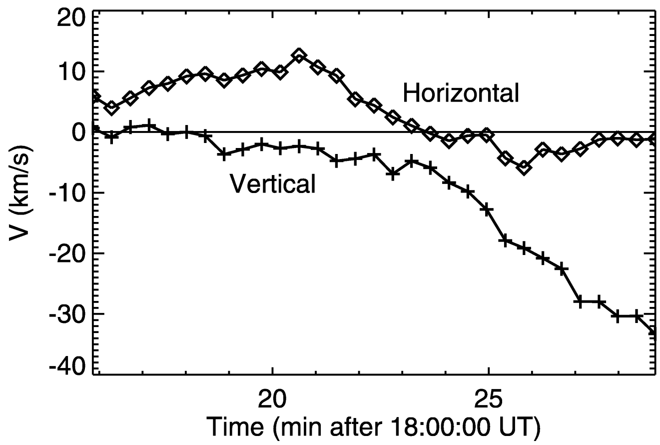

FIG. 2.—Time variations of velocity components along the trajectory of the descending blob.

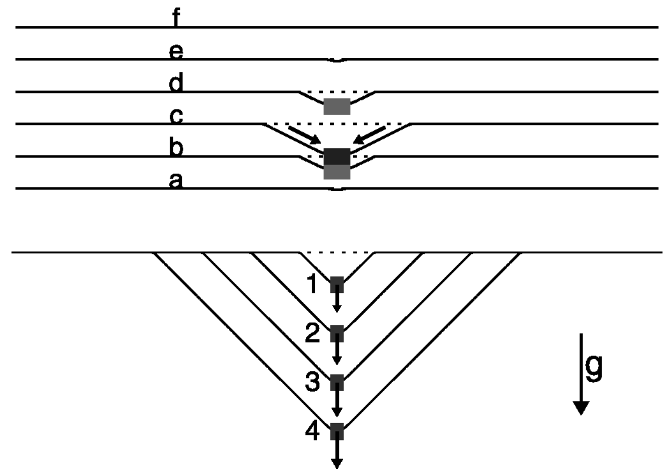

FIG. 3.—*Top*: Formation of a vertical stack of plasma (*lines*) by the distortion of initially horizontal magnetic field lines. The annotated curves represent different field lines, and the arrows indicate local plasma motions. *Bottom*: The descending motion of a blob. The numbered curves represent the time series of the same field lines.

driving these dynamic patterns. A detailed discussion of the dynamics of the prominence associated with these flows would be interesting, but is beyond the scope of this Letter.

Meanwhile, at lower altitudes the horizontal flows shed plasma blobs. As soon as bright blobs formed near the bottom of the column-like structures inside the horizontal flows, they began to descend. These descending blobs looked like those in vertical threads. This similarity suggests that the blobs descending from horizontal flows and those in vertical threads may have a common physical nature.

An important property of the blobs descending from the horizontal flows is obviously the switch of flow direction from horizontal to vertical. This characteristic is clearly manifested in the movie and is quantitatively illustrated in Figure 2. This figure shows the components of velocity along the trajectory of the blob descending from the horizontal flow as indicated by an arrow in Figure 1. The horizontal width (FWHM) of this blob is estimated to be 1.5″ (1100 km). The blob was tracked for 13 minutes with the NAVE technique.

Figure 2 clearly shows that the flow was initially horizontal at a speed of ∼10 km s^{-1} before 18:21 UT, and then turned downward after 18:23 UT, with the speed increasing with time, up to 35 km s^{-1}. It seems that the descent of the blob occurred in two stages. The former stage, before 18:23 UT is characterized by a small value of acceleration, 0.015 km s^{-2}, and the later stage by a larger value of acceleration, 0.083 km s^{-2}. These values, however, are much smaller than the solar surface gravity of 0.27 km s^{-2}, indicating that the descending motion is far from free-fall.

4. DISCUSSION

The existence of persistent horizontal flows reaching a long distance can be interpreted as observational evidence against the supposition of a predominantly vertical magnetic field, despite the dominance of vertical plasma structures. Supposing that magnetic field is predominantly vertical, its vertical magnetic flux will have to be compressed by the observed horizontal flows, introducing the Lorentz force, which will act against the flows. The problem is that it is very hard for the flows to reach a long distance in such a field configuration, unless the initial speed is high enough (in fact, this is not the case). In addition, how can the flows remain horizontal for a while without descending if magnetic fields are predominantly vertical? Horizontal flows along horizontal magnetic fields, in contrast, will not suffer from these problems, so it is likely that the observed horizontal flows are more or less field-aligned.

Is then the existence of shedding plasmas any evidence for vertical field lines? It may *not* be. This is because it is very difficult to think of physically reasonable field line geometry that would explain the observations. If the horizontal flows are directed along horizontal magnetic fields and the vertically descending motions are directed along vertical magnetic fields, then the existence of plasmas shedding from horizontal flows would imply that field lines are deflected by a right angle where shedding occurs. The problem is that the observed starting points of plasma shedding were not uniquely specified, but spatially scattered, which is inconsistent with the picture of a prespecified field line geometry. Thus, we think that the flows of shedding plasma are not field-aligned, and magnetic fields are not vertical.

Note that we have inferred predominantly horizontal magnetic fields indirectly from the characteristics of flows seen in Hα observations. Since no direct magnetic field observations are available, other interpretations of the observational results are in principle possible.

If magnetic fields are predominantly horizontal, as we inferred from the observed persistent horizontal flows, how then can we understand the formation of the column-like plasma structures and the descending motion of the shedding blobs we observed? These column-like structures are similar to vertical threads, and the descending motion of the shedding blobs to downflows in vertical threads. We think that these features can be fairly well explained with the models that have been proposed to explain vertical threads in quiescent prominence in terms of magnetic dips in initially horizontal magnetic fields (Heinzel & Anzer 2001; Low & Petrie 2005).

The behavior of material suspended in initially horizontal magnetic fields can be conjectured from the force along the vertical direction,

$$F_z = -\rho g + \frac{B_x}{4\pi}\frac{\partial B_z}{\partial x} - \frac{\partial}{\partial z}\left(p + \frac{B_x^2}{8\pi}\right), \qquad (1)$$

where z increases upward in the vertical direction, and x represents a horizontal coordinate. The top panel of Figure 3 illustrates the formation of a vertical stack of plasma, which may be manifested as one of the observed column-like plasma structures. Our conjecture starts with the supply of mass by the observed horizontal flows. As more and more plasma is horizontally transported along an initially horizontal magnetic field line (field line *c* in Fig. 3), it is very likely that the density of plasma is locally enhanced somewhere. The density can further be enhanced by condensation of surrounding plasmas (Choe & Lee 1992; Drake et al. 1993). If the enhancement of density is large enough, gravity, the first term on the right-hand side of equation (1), will sag the magnetic field line, creating a magnetic dip. The sagging introduces magnetic tension (the second term), and as a result there competition emerges between downward gravity and upward magnetic tension. If there is enough material, the sagging of the field line will make nearby plasma slide down to the dip, which will further sag the field line. Once a magnetic dip is formed at a spatial point in a horizontal field line, it is likely that other field lines will sag too, resulting in a vertical succession of magnetic dips. This effect is due to the force of magnetic pressure gradient (the third term of eq. [1]). For instance, we find from the figure that the magnetic pressure of the volume between field lines *c* and *d* becomes lower than that between field lines *d* and *e*, introducing the downward force of magnetic pressure gradient in field line *d* (note that the magnetic pressure at a point is proportional to the square of the flux density). Thus, field line *d* also sags. If enough material is supplied to this field line, the sagging will develop into a dip. Similarly, the increased magnetic pressure of the volume between field lines *b* and *c* produces the downward force of the magnetic pressure gradient in field line *b*, able to produce a dip in field line *b*. As a consequence, a vertical stack of magnetic dips may be formed, which may appear as a vertical thread.

The bottom panel of Figure 3 illustrates how a blob of plasma can descend in the presence of initially horizontal magnetic fields. We remark that this picture is not a new idea, but has been adapted from Figure 8 of Low & Petrie (2005). The descending motion of a blob can be explained by the excess of downward gravity over the upward Lorentz force, never reaching an equilibrium. One important property of this motion is that it is in the direction perpendicular to the field lines, and hence it transports the field lines downward. According to this picture, the lower the blob moves down, the larger the scale of the sagging. Note that the sagging of the field line produces an upward force of magnetic tension, though not so strong as gravity, so that the descending motion is not a free fall, which is consistent with our observations. Recall that the shedding plasma shown in Figures 1 and 2 is accelerating downward, so that it is not in a magnetohydrostatic equilibrium, implying an excess of downward gravity over upward magnetic tension. An interesting feature is that since the acceleration is much slower than gravity, the two terms must be roughly balanced, and its magnetic structure may not differ much from a magnetohydrostatic configuration. With this magnetohydrostatic approximation, the horizontal width w of the shedding blob is expected to be determined by the ratio of the horizontal B_x to the vertical component B_z of magnetic field, as well as pressure scale height H_p: $w = 4(B_x/B_z)H_p$ (Kippenhahn & Schlüter 1957; Heinzel & Anzer 2001; Low & Petrie 2005). Using the values of $w = 1100$ km (previous section) and $H_p = 300$ km (e.g., Tandberg-Hanssen 1995), we find that B_z is comparable to B_x, meaning that the field lines just outside the blob are inclined to the vertical at about 45°, similar to the field lines drawn in the bottom panel of Figure 3.

We think that models of magnetic dips can explain the diverse appearance of solar prominences. The most important parameters in these models are the strength of the initial magnetic field, B_x, and the column mass of the loaded plasma, M. The newly introduced vertical component of the magnetic field, B_z, in the magnetic dip in equilibrium is then determined by the ratio of these two quantities: $B_z = 2\pi gM/B_x$. This equation means that prominences supported against initially weak magnetic field B_x have high values of B_z, which means that the field lines' dip is deep. Another consequence is that the horizontal width of the plasma structure supported by such a magnetic dip, $4(B_x/B_z)H_p$, is thin. Vertical thin threads hence naturally arise in weak magnetic fields. This explains the fine structures in quiescent prominences. In contrast, if the initial field is strong, the dips appear to be shallow and wide, resulting in horizontal threads (or fibrils) aligned with the local magnetic field. This explains the morphology of active region prominences.

In conclusion, our results are consistent with the traditional models that vertical threads in quiescent prominences are stacks of plasma supported against gravity by the sagging of initially horizontal magnetic field lines.

We greatly appreciate the referee's constructive comments. This work was supported by the Korea Research Foundation Grant funded by the Korean Government (KRF-2005-070-C00059).

REFERENCES

Berger, T. E., et al. 2008, ApJ, 676, L89
Casini, R., López Ariste, A., Tomczyk, S., & Lites, B. W. 2003, ApJ, 598, L67
Chae, J., & Sakurai, T. 2008, ApJ, in press
Choe, G. S., & Lee, L. C. 1992, Sol. Phys., 138, 291
Drake, J. F., Mok, Y., & van Hoven, G. 1993, ApJ, 413, 416
Engvold, O. 1976, Sol. Phys., 49, 283
———. 1998, IAU Colloq. 167, New Perspectives on Solar Prominences, ed. D. F. Webb, B. Schmieder, & D. M. Rust (San Francisco: ASP), 23
Heinzel, P., & Anzer, U. 2001, A&A, 375, 1082
Jensen, E. 1990, IAU Colloq. 117, Dynamics of Quiescent Prominences (Berlin: Springer), 129
Kippenhahn, R., & Schlüter, A. 1957, Z. Astrophys., 43, 36
Kosugi, T., et al. 2007, Sol. Phys., 243, 3
Leroy, J. L. 1978, A&A, 64, 247
———. 1989, in Dynamics and Structure of Quiescent Solar Prominences (Dordrecht: Kluwer), 77
Leroy, J. L., Bommier, V., & Sahal-Brechot, S. 1983, Sol. Phys., 83, 135
Low, B. C. 1982, Sol. Phys., 75, 119
Low, B. C., & Petrie, G. J. D. 2005, ApJ, 626, 551
Mackay, D. H., & Galsgaard, K. 2001, Sol. Phys., 198, 289
Malville, J. M. 1976, Sol. Phys., 50, 79
Merenda, L., Trujillo Bueno, J., Landi Degl'Innocenti, E., & Collados, M. 2006, ApJ, 642, 554
Tandberg-Hanssen, E. 1995, The Nature of Solar Prominences (Dordrecht: Kluwer)
Tsuneta, S., et al. 2008, Sol. Phys., 249, 167
Zirker, J. B. 1989, Sol. Phys., 119, 341
Zirker, J. B., Engvold, O., & Martin, S. F. 1998, Nature, 396, 440
Zirker, J. B., Engvold, O., & Yi, Z. 1994, Sol. Phys., 150, 81