Theory of solar prominences

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Abstract. We discuss the physical mechanisms for the formation, the gravitational support, and the eruption of solar prominences and filaments. We show that the formation of cool mass in the coronal is due to the thermal non-equilibrium of coronal loops that are heated preferentially near their footpoints. The gravitational support can be understood as a direct consequence of the differential shearing of a three-dimensional magnetic field. Finally, the eruption can be explained by the "breakout" model, in which magnetic reconnection leads to the explosive expansion of the sheared prominence field. We present results from numerical simulations which confirm each of these three fundamental mechanisms. Based on this work, we conclude that we are now approaching a true understanding of the basic physics of solar prominences.

Keywords: solar prominences, filament eruptions, magnetic reconnection

1. Introduction

Solar prominences and filaments are beautiful phenomena both in their appearance and in their physics (e.g., Tandberg-Hanssen 1995). They are commonly observed in Hα as large masses ($\sim 10^{16}$ g) of dense ($> 10^{11}$ cm^{-3}) chromospheric plasma floating high up in the tenuous ($\sim 10^{9}$ cm^{-3}) million-degree corona. Although most prominences have lifetimes of order days, some especially quiescent structures can last for months. Surprisingly, most prominences disappear by "falling up" as a filament eruption rather than by falling down onto the chromosphere. Large coronal mass ejections and two-ribbon flares are usually accompanied by prominence/filament eruption, consequently prominences play a key role in space weather. We conclude that understanding the fundamental physics of solar prominences is crucial not only for advancing our comprehension of solar activity, but also for understanding the Sun-Earth connection.

There are three obvious basic questions that must be addressed if we are to understand prominences/filaments:

1. How is the dense prominence mass supported against gravity?

2. Why does cool prominence mass form in the hot corona?

3. What causes prominences to erupt into interplanetary space?

We show below that the answer to each of these three questions lies in spatial inhomogeneity — of photospheric motions, of coronal heating, and of magnetic flux.

2. Gravitational support

Since the typical lifetime of prominence material is many orders of magnitude larger than the gravitational free-fall time, it is generally believed that the material must somehow be supported by the magnetic field (e.g., Kippenhahn & Schluter 1957; Kuperus & Raduu 1974). But in order for a cool condensation to sit stably on some field line, the field line must have a concave up geometry in the corona. This is, of course, completely opposite from what would be expected for a potential field due to a bipolar flux distribution at the photosphere. It is possible to obtain concave up field lines for quadrupolar flux distributions, but prominences are generally associated with bipolar regions. They overlie a single photospheric neutral line.

These considerations have led many authors to consider fairly complex models for the prominence magnetic field, such as models which involve twisted flux ropes embedded in some overlying bipolar arcade. The flux ropes are presumed to somehow form or emerge from below into the corona. But, prominences are very common and, hence, their magnetic structure must be straightforward to obtain. Furthermore, the twisted field indicative of a flux rope has never been observed, to our knowledge, except during eruption, even by the exquisite observations by TRACE. On the other hand, shear is clearly observed in both active region and quiescent prominences (e.g., Martin 1990; Schmieder et al 1996), and is strikingly visible in the TRACE images (Title, *private communication*).

We have shown how the concave up field line geometry necessary for prominence support can be simply explained as a natural consequence of spatially localized photospheric shear in 3D (Antiochos, Dahlburg & Klimchuk 1994; DeVore & Antiochos 2000). Figure 1, which is obtained from one of our 3D force-free field simulations, presents the essential features of our model. We start with a current-free dipole field and apply a shear flow at the photosphere that is concentrated near the neutral line of the dipole. The shear flow is parallel to and changes sign across the neutral line, and is large only near the neutral line. Note that this form for the magnetic shear is an observational fact (e.g., Gary et al 1987; Schmieder et al 1996), but its actual source is not important for our model. We use footpoint motions only because they are convenient to implement numerically. The shear could as well be created below the photosphere by convective motions, or the shear could be due to reconnection. The gray bottom grid in Figure 1 corresponds to the photosphere, and the color contours on this grid correspond to magnitude of the normal component of the field at the photosphere. The red – yellow contours on the near side of the Figure correspond to positive polarity, and the blue – green on the far side correspond to negative polarity. The form of the photospheric shear can be seen from these contours. The contours on opposite sides of and near the neutral line are stretched out in opposite directions.

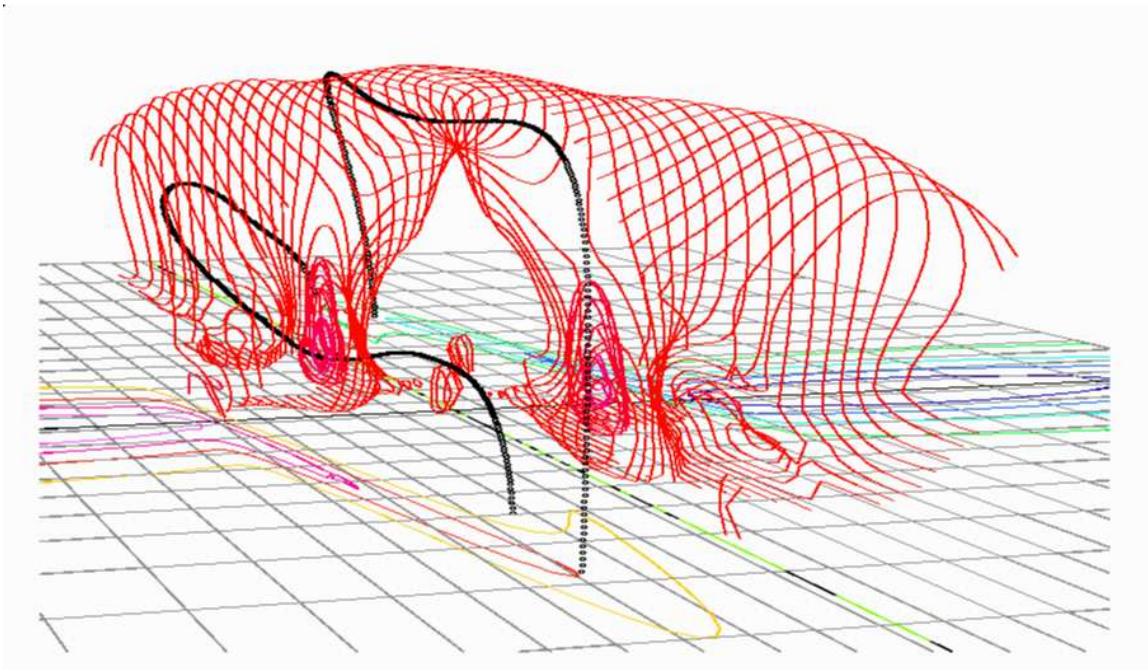

Figure 1: 3D sheared magnetic field model of a solar prominence.

Also shown in the Figure are two field lines whose footpoints lie in the strong shear region — thick black lines. Note that the lines are concave up in their midsections and, therefore, can support cool dense material in the corona. The origin of these "dips" in the field lines is due to the effect of the overlying unsheared field lines, which act to constrain the expansion of the sheared lines. The constrainment is strongest near the center of the system, where the photospheric flux is strongest, resulting in a dip near the center of the sheared lines. In other words, the unsheared flux pushes down harder on the sheared field lines near their middle, distorting them into a concave up shape.

The concave up regions of the field are shown by the mass of red contours. They correspond roughly to the shape of the prominence that this model predicts. Note that this shape has legs and an arch, very similar to what is observed for quiescent prominences. Furthermore, the model reproduces the inverse polarity that is observed in most prominences and also the characteristic "sigmoidal" shape for the field. Figure 2 shows the same force-free field as in Figure 1, but now the viewpoint is from above and we plot contours of inverse polarity. It is evident that the field lines have a sigmoidal shape and that the prominence is inverse polarity over the bulk of its volume. Another interesting agreement with observations (Martin & McAllister 1997) is that if we consider the neutral line to correspond to the main body of this prominence, we see from Figure 2 that the legs are "left-bearing", and from the form of the shear on the photosphere, the prominence is sinistral.

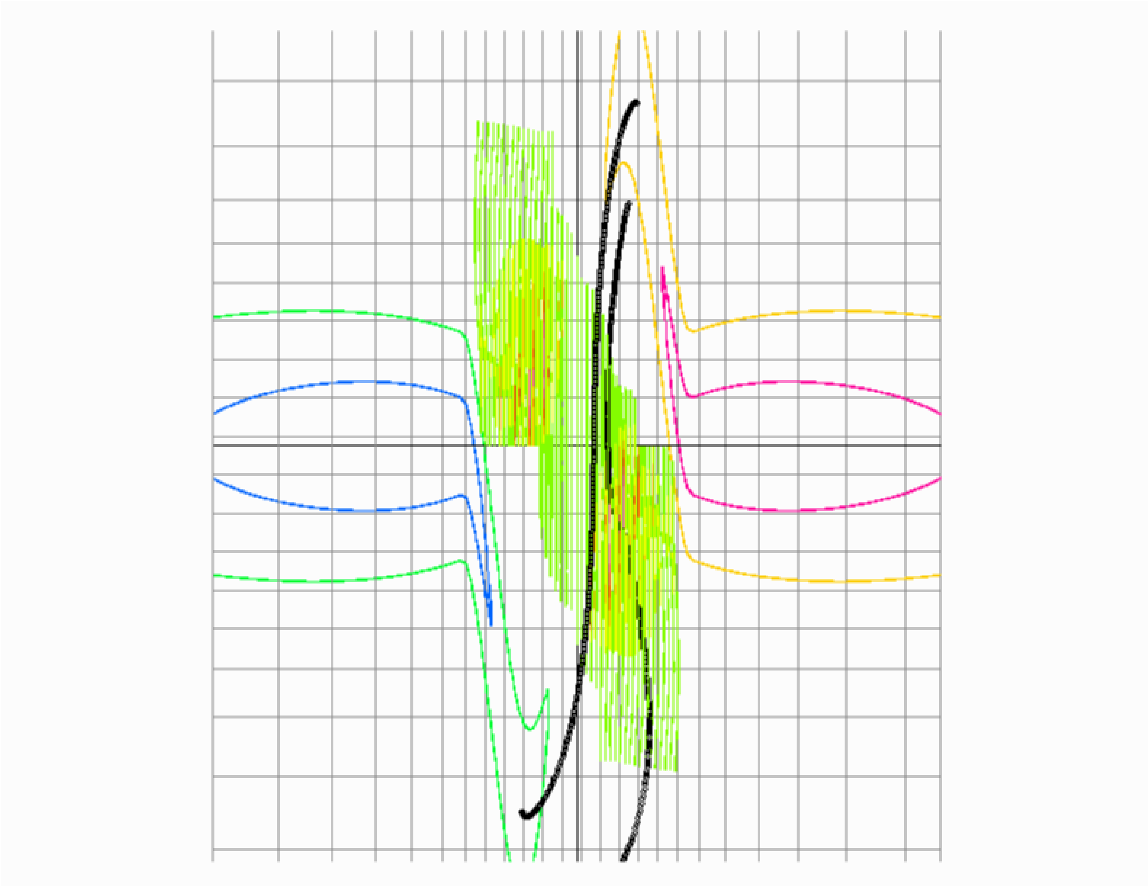

Figure 2: The prominence model of Figure 1 viewed from above.

In summary, this simple model appears to explain the origin of concave up field lines and all the major observed global features of prominence. All that the model requires is neutral line shear — twisted flux ropes need not apply! Of course, one could elaborate on our 3D shear model by adding small parasitic polarity regions (e.g. Aulanier & Demoulin 1998) or by including the effects of reconnection (DeVore & Antiochos 2000), but we now have the basic answer to our first question concerning gravitational support: Shear localized near the neutral line produces concave up field lines in 3D.

3. Condensation formation

In the previous section we considered the support of prominence condensations and argued that a sheared 3D field is likely to have field lines with dips in which the condensations can lie stably. The question remains, however, as to why condensations should form on such field lines. There is no obvious reason to expect a condensation from the usual models for coronal heating, even if the flux tube has a dip. For typical coronal temperatures ($T > 10^6$

K), the gravitational scale height ($> 5 \times 10^9$ cm) is much larger than the expected depth of a field line dip. Thus, as far as hot coronal plasma is concerned, gravity is negligible and the presence of a dip would have only a minor perturbation on the plasma structure.

It is clear, however, that prominence condensations are far from negligible. In fact, assuming a condensation size of $\sim 10^8$ cm and a density for the cool material $> 10^{11}$ cm^{-3}, we find that the mass of an individual condensation can be large compared to the hot coronal mass in the magnetic flux tube that the condensation occupies. Consequently, the condensations cannot be due to a simple thermal instability (e.g., Antiochos et al. 1985; Klimchuk, Antiochos & Mariska 1987) and cooling of coronal material, but must involve the transfer of chromospheric plasma into the corona.

Numerous models have been proposed for the formation of prominence condensations (e.g., Pikel'ner 1971; Engvold & Jensen 1977; Priest & Smith 1979; Ribes & Unno 1980; An, Bao, & Wu 1986; Poland & Mariska 1986; Mok et al., 1990), many involving the initiation of a condensation *via* an abrupt decrease in the coronal heating rate. Although this is a straightforward and attractive idea, it suffers a major drawback in that a large decrease in the heating inevitably results in a large decrease in the coronal mass. When the heating is decreased, loop material simply drains back onto the chromosphere (Poland & Mariska 1986), which is exactly the opposite of what is needed for a massive condensation in the corona.

The problem with invoking a heating decrease can also be seen by examining the usual scaling laws for quasi-static coronal loops (e.g., Rosner, Tucker & Vaiana 1978; Craig, McClymont & Underwood 1978; Vesecky, Antiochos & Underwood 1979). One finds that the coronal density, $N \propto E^{4/3}$ for a heating rate E that is constant per unit mass. Consequently, loops with decreased heating are expected to end up with low masses, rather than the large mass needed for prominence condensations.

We have proposed a novel solution to the problem of obtaining a massive condensation in a dipped loop (Antiochos & Klimchuk 1991). The key idea is that the heating has a strong spatial dependence; in particular, it is concentrated near the chromospheric footpoints of the loop, far from the dip. The effect of the localized heating is to drive a flow from both chromospheric footpoints into the dipped portion of the loop. This is most easily seen for the case of a loop that is symmetric about its midpoint. Due to the symmetry and to the presence of the dip, each loop half is physically similar to a complete, but asymmetric coronal loop that has a heating rate strongly localized near only one footpoint. It is well known that the only equilibrium solution for an asymmetric loop model with a localized heating near one base point is a steady-state flow from the heated footpoint towards the other one (Boris & Mariska 1982; Mariska & Boris 1983). Due to this flow the density and, therefore, the radiative losses in the dipped portion of the loop continue to increase until a thermal loss-of-equilibrium occurs and a large mass cools catastrophically to chromospheric temperatures.

We have verified our thermal non-equilibrium model for prominence condensation formation by a number of detailed numerical simulations (Antiochos & Klimchuk 1991; Dahlburg et al 1998; Antiochos et al 1999; Antiochos, MacNeice & Spicer 2000). Figure 3 shows the results of our most recent simulation. We considered a geometrically-symmetric dipped flux tube of total length 220,000 km, that initially had a spatially uniform heating

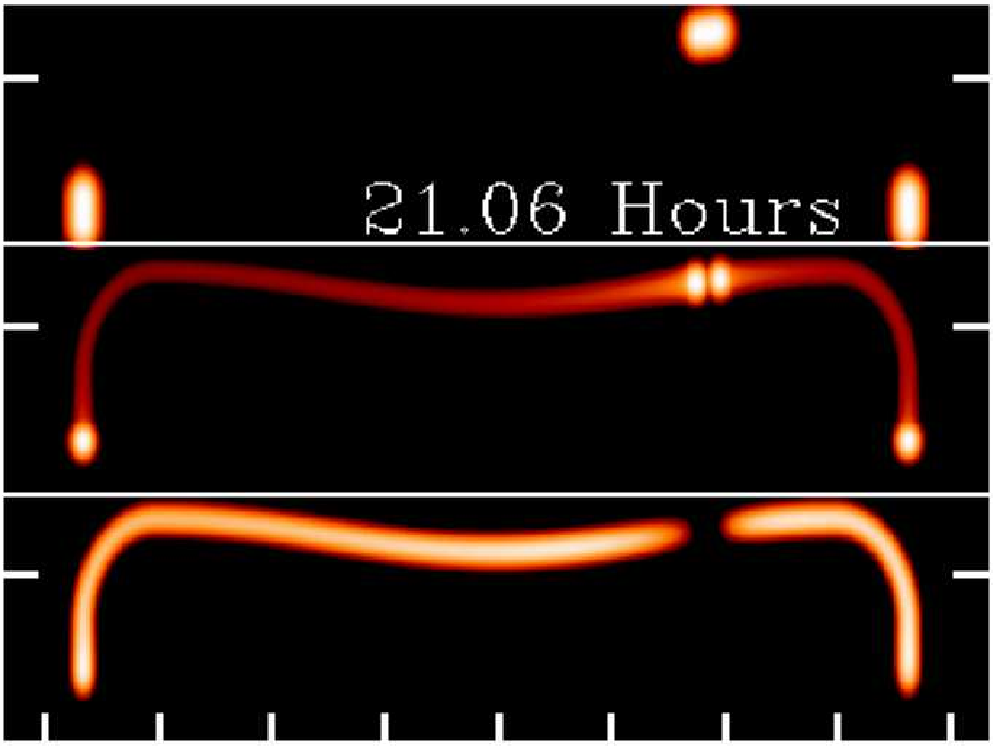

Figure 3: The Mg X (bottom panel), O V (middle panel) and H_α emission predicted by our prominence condensation model.

rate and was at coronal temperatures ($T \sim 10^6$ K) everywhere except at the footpoints. Then we applied a spatially localized heating that was maximum at the chromospheric footpoints and had a scale height of 10,000 km. In order to break any artificial symmetry, the localized heating at the right leg was taken to be 75% of that at the left. After 21 hours, the loop emission in Mg X, O V, and H_α is shown in Figure 3. It is evident that a prominence condensation, bright in H_α has formed. The condensation is bounded on each side by a transition region, visible in O V emission. Also, the condensation appears as a gap in the million degree Mg X radiation.

An interesting result is that the condensation does not sit stably in the concave up portion of the loop. Instead it moves toward the right apex with an average velocity of order 5 km/s and falls down onto the right chromosphere, (Antiochos, MacNeice & Spicer 2000). After a period of another 20 hours, another condensation forms to repeat the cycle again. Consequently, our model can account not only for the formation of condensation, but also for their recently measured dynamics (Zirker, Engvold & Martin 1998; Martin 1998). We conclude that we now have the answer to our second question concerning the origin of the mass: Prominence condensations form as a result of thermal non-equilibrium driven by a coronal heating that is spatially localized near the chromosphere.

4. Prominence eruption

Since the configuration of Figures 1 and 2 appears to be the correct magnetic structure of a prominence/filament, it is tempting to hypothesize that this configuration also leads to eruption, so that neutral line shear answers both our questions 1 and 3. In fact, the "tether cutting" model (e.g., Sturrock 1989; Moore & Roumeliotis 1992) proposes that continued shearing of this configuration will produce magnetic reconnection *below* the sheared field, thereby destroying the force balance between the sheared and overlying unsheared field and leading to an explosive eruption. Our numerical simulations of stressed bipolar fields, however, show no evidence for such eruptions (e.g., Klimchuk & Sturrock 1989; Dahlburg, Antiochos & Zang 1991; Roumeliotis et al. 1994). Recently, we have performed a very massive simulation of extreme shearing of a dipolar field, and although considerable reconnection occurred, we saw no evidence for eruption (DeVore & Antiochos 2000). The field does expand outward as a result of continued shearing, and this expansion can become exponentially fast for very large shear (e.g., Roumeliotis, Sturrock & Antiochos 1994; Mikic & Linker 1994; Sturrock, Roumeliotis & Antiochos 1995). This expansion process may well be able to account for many slow CMEs which never exceed the slow solar wind speed ≤ 400 km s^{-1}, but simple expansion cannot account for the fast $\sim 2,000$ km s^{-1} CME/eruptive flares associated with strong δ-sunspot regions. These appear in the field of view of the LASCO coronagraphs on SOHO with velocities much greater than the fast solar wind, and *slow down* in the upper corona (Sheeley, *private communication*).

CME/eruptive flares must be driven by an explosive release of magnetic energy, but the configuration of 1 does not appear to exhibit this type of behavior. The fundamental problem has been elucidated by Aly (1984,1991) and Sturrock (1991): a magnetically dominated flux system cannot have more energy in a closed configuration than in its fully open state. Consequently, the sheared field in our prominence model (Figures 1 and 2) cannot contain enough energy to erupt spontaneously, forcing the overlying unsheared field outward towards infinity as well.

Recently, we have proposed an idea "magnetic breakout" that solves this long-standing problem (Antiochos 1998; Antiochos, DeVore & Klimchuk 1999). The key to solving the energy limitation is to remove the unsheared overlying flux while keeping it closed at all times. This is impossible for a bipolar flux system like the field of Figures 1 and 2, but in a multipolar flux system, magnetic reconnection can do precisely this trick. Figure 4 shows the essential physics of our model. The magnetic topology consists of four distinct flux systems. Strongly sheared (dark blue) field lines are emerging at the equatorial neutral line and pushing outward. These field lines, which correspond to dipped prominence field, are being held down by the overlying, unsheared (light blue) field lines that are part of the same flux system. If this were the only flux system present, then no eruption could occur, but reconnection in the corona *above* the blue system converts blue and red flux into green flux, thereby removing it from overlying the equatorial neutral line and allowing the sheared field to "breakout". This reconnection is evident in the Figure. Our simulations (Antiochos, DeVore & Antiochos 1999) have verified that this model does circumvent (but not violate) the Aly-Sturrock energy limit and produce the magnetic free energy required to account for fast eruptions. Note also that, in agreement with observations, the lowest lying sheared field — down to the photospheric neutral line — can open up with the breakout model, a result which is not possible with tether cutting.

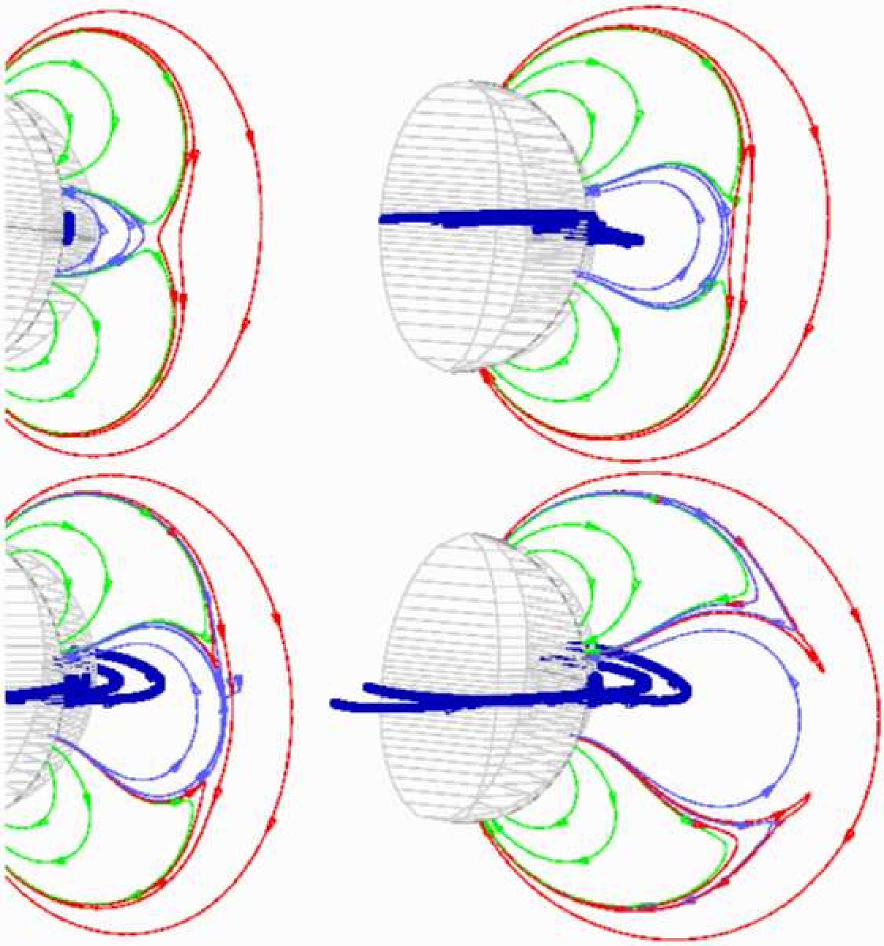

Figure 4: Magnetic field evolution from a "breakout" simulation.

The most important feature of the breakout model is that it produces an explosive eruption. The rate of upward expansion is controlled by the rate of reconnection at the null which, in turn, is controlled by the thickness of the current sheet at the null. But as the system expands outward, the current sheet becomes thinner and thinner, so that the reconnection proceeds ever faster. Hence, there is a natural feedback process between reconnection and expansion which leads to an exponentially growing evolution. This feedback process is evident in Figure 4. Initially, and for low shear, the red and blue field lines across the null are well separated, so that any reconnection that occurs is too slow to be significant to the evolution. Therefore, the shear and the magnetic free energy can build up to appreciable levels. As the shear builds up, however, the system expands outward and the current sheet region at the null becomes longer and thinner, which leads to faster reconnection. The reconnection removes unsheared constraining flux, leading to faster expansion. We conclude, therefore, that the configuration of Figure 4 represents a robust process for obtaining explosive eruption.

Another attractive feature of our "breakout" model is that it can explain why large eruptive flares usually are associated with the appearance of active region magnetic fields in certain unusual configurations: the so-called δ-spot active regions (Zirin 1988), in which two or more sunspot umbra of opposite polarity form within the same penumbra. Simple bipolar regions, on the other hand, are usually inactive. The key point is that the magnetic complexity of, at least, a δ-spot is needed in order to have in 3D a four flux system that is equivalent to the topology of Figure 4 (Antiochos 1998).

Although a great deal of work remains to be done on the breakout model, especially in 3D, the results so far are convincing. We believe that we now have the basic answer to our third question on the cause of prominence eruption: Reconnection of overlying unsheared flux with neighboring flux systems allows the sheared core field to explode outward.

5. Discussion

An interesting conclusion of the results described above is that in each case, spatial inhomogeneity played a vital role. For the gravitational support question, it was the spatial localization near the neutral line of the photospheric shear that led to the formation of concave up field lines in the corona. For the question of condensation formation, it was the localization of the heating near the chromosphere that led to thermal non-equilibrium. For the question of eruption, the multipolarity structure of the photospheric field was needed in order for reconnection and breakout to occur. The conclusion that inhomogeneity plays a key role in the physics of prominences emphasizes that large-scale numerical calculations are likely to be essential for understanding the Sun's activity.

Finally, we should emphasize that although we have presented an answer to the three basic questions concerning prominences, each of our answers has raised another, and perhaps more basic, question:

1. What is the origin of the magnetic shear?
2. What is the mechanism for heating coronal loops?
3. What is the nature of 3D reconnection?

It may well turn out that these far-reaching questions will also be answered by studying that beautiful phenomenon known as solar prominences.

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References

Aly, J.J. 1984, ApJ, 283, 349

Aly, J.J. 1991, ApJL, 375, L61

An, C.-H., Bao, J.J., & Wu, S.T. 1986, in Coronal and Prominence Plasmas, ed. A. Poland (NASA CP-2442), 51

Antiochos S.K., Shoub, E.C., An, C.-H., & Emslie A.G. 1985, ApJ, 298, 876

Antiochos S.K. & Klimchuk, J.A. 1991, ApJ, 378, 372

Antiochos, S.K., Dahlburg, R.B. & Klimchuk, J.A. 1994, ApJL, 420, L41

Antiochos, S.K. 1998, ApJL, 502, L181

Antiochos, S.K., DeVore, C. R. & Klimchuk, J. A. 1999, ApJ, 510, 485

Antiochos, S.K., MacNeice, P. J., Spicer, D. S., &

Klimchuk, J.A. 1999, ApJ, 512, 985

Antiochos, S.K., MacNeice, P.J., & Spicer, D.S. 2000, ApJ, in press

Aulanier, G. & Demoulin, P. 1998, A&A, 329, 1125

Boris, J.P., & Mariska, J. T. 1982, ApJ, 258, L49

Craig, I.J.D., McClymont, A.N., & Underwood, J.H. 1978, A&A, 70, 1

Dahlburg, R.B., Antiochos, S.K., & Zang T.A. 1991, ApJ, 383, 420

Dahlburg, R.B., Antiochos, S.K., & Klimchuk, J.A. 1998, ApJ, 495, 485

DeVore, C.R. & Antiochos, S.K. 2000, ApJ, in press

Engvold, O., & Jensen, E. 1977, Solar Phys., 52, 155

Gary, G.A., Moore, R.L., Hagyard, M.J., Haisch, B.M. 1987, ApJ, 314, 782

Greene, J.M. 1988, *J. Geophys. Res.*, 93, 8583

Kippenhahn, R. & Schluter, R. 1957, *Z. Astrophys.*, 43, 36

Klimchuk, J.A., Antiochos, S.K., & Mariska, J.T. 1987, ApJ, 320, 409

Klimchuk, J.A. & Sturrock, P.A. 1989, ApJ345, 1034

Kuperus, M. & Raadu, M.A. 1974, A&A, 31, 189

Mariska, J.T., & Boris, J.P. 1983, ApJ, 267, 409

Martin, S. 1990, in IAU Coll. 117, *Dynamics of Quiescent Prominences*, ed. V. Rudzdjak & E. Tandberg-Hanssed (Lecture Notes in Physics, Vol 363), 1

Martin, S. & McAllister, A.H. 1997, in Geophys. Monograph 99, *Coronal Mass ejections*, ed. N. Crooker, J. Joselyn, & K. Feynman, (Washington: AGU), 127

Martin, S.F. 1998, Solar Phys., 182, 107

Mikic, Z. & Linker, J.A. 1994, ApJ, 430, 898

Mok, Y., Drake, J.F., Schnack, D.D., & Van Hoven, G. 1990, ApJ, 359, 228

Moore, R.L. & Roumeliotis, G. 1992, *Eruptive Solar Flares*, ed. Z. Svestka, B.V. Jackson, & M.E. Machado (Berlin: Springer)

Pikel'ner, S.B. 1971, Solar Phys., 17, 44

Poland, A.I. & Mariska, J.T. 1986, Solar Phys., 104, 303

Priest, E.R., & Smith, E.A. 1979, Solar Phys., 64, 217

Ribes, E. & Unno, W. 1980, A&A, 91, 129

Rosner, R., Tucker, W.H., & Vaiana, G.S. 1978, ApJ, 220, 643

Roumeliotis, G., Sturrock, P.A., & Antiochos, S.K. 1994, ApJ, 423, 847

Schmieder, B., Demoulin, P., Aulanier, G., & Golub, L. 1996, ApJ, 467, 881

Sturrock, P.A. 1991, ApJ, 380, 655

Sturrock, P.A. 1989, Solar Phys., 121, 387

Sturrock, P.A., Roumeliotis, G. & Antiochos, S.K. 1995, ApJ, 443, 804

Tandberg-Hanssen, E. 1995, *The Nature of Solar Prominences*, (Dordrecht: Kluwer)

Vesecky, J.F., Antiochos, S.K., & Underwood, J.H. 1979, ApJ, 233, 987

Wolfson, R. 1993, ApJ, 418, 382

Zirker, J.B., Engvold, O., & Martin, S.F. 1998, Nature, 396, 440

Zirin, H. 1988, Astrophysics of the Sun (Cambridge Univ. Press: Cambridge)

Discussion

K.D. Leka: The model of the CME, the overlying field lines that you showed spanned from solar north to solar south with the prominence at the equator. Is this model and its general picture of the magnetic configuration/complexity applicable also to a single hemisphere, perhaps an active region and the surrounding overlying fields?

S. Antiochos: The breakout model does, indeed, apply to an active region. In fact, I believe that it is more suitable for fast CMEs originating from active regions than from quiet regions. I have argued (Antiochos 1998), that the topology of Figure 4 is exactly that of a delta-sunspot region. These are well-known to be the sources of strong eruptive flares.

N. Nitta: How does your model compare with the three-part structure of a CME? Why is the core slower than the frontal loop?

Is the strong field really a necessary condition for a CME, when we know that a major event (like the one on 14 April 1994) can happen in a quiescent area?

S. Antiochos: Since our code cannot follow the evolution beyond the initial acceleration phase, I cannot say whether a three part structure forms in the model or whether the core would expand slower than the front. However, it seems likely since the erupting field of Figure 4 divides naturally into unsheared-outer and sheared-core field.

A strong field is necessary for a fast CME, $>$ 1000 km/s. Slow CMEs which accelerate only up to slow solar wind speeds do not need strong field.