V - Conclusion

GENERAL CONCLUSION OF THE SYMPOSIUM

Nature of Prominences and their role in Space Weather
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Prominences: Conference Summary and Suggestions for the Future

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Abstract. In this conclusion to the conference, I shall attempt to summarise what we knew before about solar prominences and what we have learnt during the conference (mainly from the review talks), as well as to make suggestions for their future study.

Keywords. Sun: prominences, Sun: filaments, Sun: activity, Sun: coronal mass ejections (CMEs), Sun: magnetic fields.

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1. Introduction: Prominence Formation

We have been treated to an exciting and well delivered set of talks. Clearly, prominences are intriguing and fascinating, with many secrets to reveal to us (Fig. 1). I would in particular like to thank my Paris friends such as Pierre and Nicole Mein, Zadig Mouradian, Mme Martres and Serge Koutchmy, for introducing me to prominences when I first visited in the 1970's, and to Brigitte Schmieder and Jean-Marie Malherbe for continuing this interest when I met them at Hvar and La Palma in the 1980's.

Three mechanisms for prominence formation have been proposed, namely, condensation by radiative instability or non equilibrium, levitation and injection by reconnection. At this meeting, Tom Berger gave a convincing observation from SDO/AIA of radiative condensation and also proposed a new mechanism of magneto-thermal convection, inspired by amazing movies from SDO and numerical experiments. Also, Manuel Luna presented a talk prepared by Judith Karpen of impressive multi-thermal models for prominences.

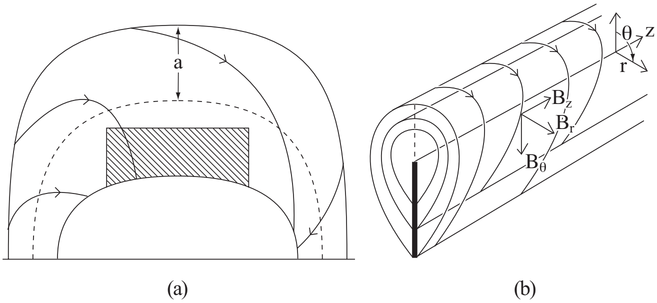
The question "How do prominences form?" is still open and needs detailed modelling as well as new ideas. A related problem is to determine how they are maintained. What is the mass circulation, both the supply and the loss? What is the engine or driver for the flow? Jack Carlyle has made a start towards addressing this issue and is to be congratulated on winning the poster prize.

2. What is the Plasma/Magnetic Structure?

It was known before that the prominence density and temperature are typically a hundred times larger and smaller, respectively, than the surrounding corona. Also, most prominences consist of a vertical sheet suspended in a large horizontal flux rope of inverse polarity above a polarity inversion line (Fig. 2). One way of forming such a flux rope is for it to emerge already twisted near a polarity inversion line (PIL). Another is for the twist to be built up by flux cancellation below a prominence at the PIL (van Ballegooijen and Martens 1989).

An important realisation has been the importance of a coronal cavity around a prominence, as reviewed by Sarah Gibson (this volume) (Fig. 3). She described the range of

Figure 1. An erupting prominence seen by SDO/AIA (courtesy NASA/SDO science team).



(a) (b)

Figure 2. The overall structure of a prominence sheet within a large horizontal flux rope, from (a) the side and (b) the end, according to the Flux-Rope Model (Priest *et al.* 1989).

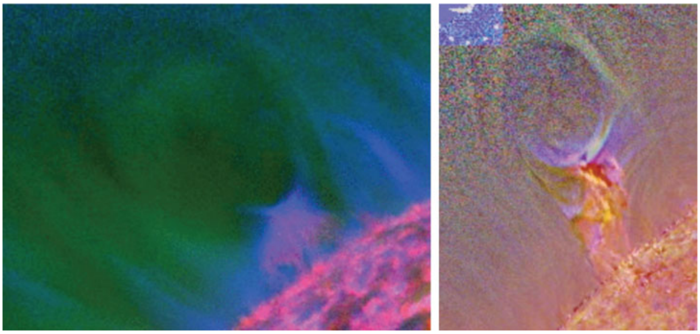


Figure 3. (a) A prominence cavity and (b) an inner flux rope observed by Alan Title (this volume), courtesy NASA/SDO science team.

sizes, the fact that they form a funnel, the density depletion by 25–30%, the substructure and the multi-thermal dynamic nature, with flows of 5–10 km s^{-1}.

Future questions are: how much mass is provided by the flows? How does this compare with the best estimate of mass loss from a prominence, taking account of the net flows on the limb and on the disc?

Alan Title (this volume) gave some fabulous evidence for inner flux ropes within the core of the cavity above erupting prominences (Fig. 4). They represent the continuation of the horns that are sometimes seen (e.g., Fig. 3) and represent the inner part of the classical three-part structure of a coronal mass ejection. Why do they appear? Is it that the eruption compresses the plasma in this part of the overlying flux rope and so makes it visible?

Jean-Claude Vial gave a coherent review (this volume, prepared by Susanna Parenti) of the prominence-corona transition region, which needs in future to be incorporated more into prominence modelling. Just as the transition region in a coronal loop is not a thin static region sitting between the chromosphere and corona, so its equivalent in a prominence represents dynamic plasma that is either heating up or cooling down and happens to be passing through 10^5 K.

Bruce Lites (this volume) gave his customary authoritative review of magnetic field observations. He stressed that in prominences the Hanle effect is the best way of measuring magnetic fields and summarised results from many years by Leroy, Bommier, Lopez Ariste and Kuckein. He concluded by describing a comprehensive study by Orozco Suárez *et al.* (2013) that has given magnetic field strengths of 2–30 G and horizontal field inclinations to the prominence axis of $15–25^o$. Also, Zhi Xu (this volume) described measurements from the new Chinese telescope of photospheric and chromospheric measurements of magnetic fields near an active-region filament.

Two thoughts occur. The first is that the prominence magnetic field probably consists of two parts, a large-scale field (which is what we normally measure) together with a small-scale turbulent field (whose existence is implied by the small-scale plasma structure in prominences). The second thought is that in future we need new non-force-free techniques to extrapolate from observed magnetic fields in the photosphere (which are not force-free) up through the chromosphere to the corona.

Jose-Luis Ballester (this volume) gave a comprehensive review of prominence seismology, which is a promising way of determining physical properties in prominences, such as field strength, plasma density and filling factor. However, this field is very much in its infancy and so more realistic models are expected in future. For example, although this model is a useful beginning, it is a gross oversimplification to regard a coronal loop or a prominence fibril as an isolated one-dimensional flux tube, and so much more complex models of such structures need to be built in future.

3. Why Barbs and Feet?

A key model for barbs was proposed by Aulanier and Démoulin (1998). It consists of a force-free flux rope with a series of parasitic polarities on both sides of the polarity inversion line. Fig. 4a shows the photospheric polarities viewed from above, including the parasites, together with locations where the prominence plasma is expected to accumulate in magnetic dips: in particular, a series of barbs is produced above the parasites. Vertical cross sections across the prominence reveal an O-type topology with a bald patch at locations between the parasites and a flat field joining two X-points above the parasites (Fig. 4b, c).

Aad Van Ballegooijen gave a superb review of prominence magnetic structure, concluding that a flux rope model works well for explaining many aspects of prominences except for the vertical threads: for example, predicting barbs, describing the formation of the flux rope and producing the horns and inner flux rope above a prominence observed by SDO/AIA. The magnetic field of a prominence is distorted by gravity when the field is weak (Hillier and van Ballegooijen 2013) and the flux-rope insertion model is useful for modelling particular prominences (Su and van Ballegooijen 2013).

In future, it will be interesting to determine whether prominences are located in current sheets with the field either side being vertical or possessing a horizontal component. Also,

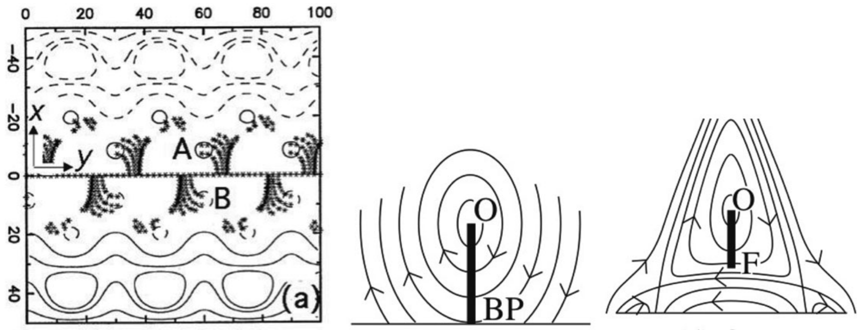


Figure 4. A force-free flux rope model with parasitic polarities, showing (a) the photospheric flux pattern viewed from above together with the locations (crosses) of dips and (b), (c) vertical sections across the prominence at two locations (Aulanier and Démoulin 1998).

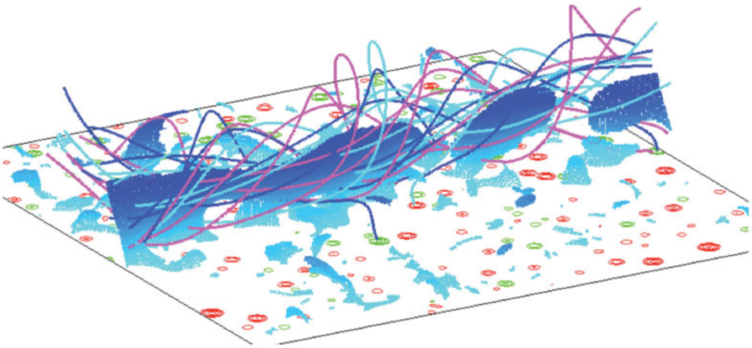


Figure 5. A twisted flux-rope model due to Su and van Ballegooijen (2013).

it is important to ensure that models are consistent with both disc and limb observations, which sometimes appear contradictory at first sight.

4. The Formation of Flux Ropes along a Polarity Inversion Line

Prominences possess a global chirality pattern, being mainly dextral in the northern hemisphere and sinistral in the southern hemisphere (Martin *et al.* 1994). Also, the shear is concentrated around the polarity inversion line (Schmieder *et al.* 1996). A way in which the chirality of a prominence is produced was suggested in the Dextral and Sinistral Model (Priest *et al.* 1996) and this was later developed by van Ballegooijen *et al.* (2000) in the mean-field model for filament channel formation. The model includes a flux-transport model for the evolution of the radial photospheric magnetic field in response to flux emergence, differential rotation, meridional flow and supergranular diffusion. It also shows how the coronal magnetic field evolves through a series of nonlinear force-free fields in response to the photospheric evolution.

Applying this to observed magnetic fields was highly effective (Mackay and van Ballegooijen 2005; Yeates *et al.* 2008). In particular, the model predicts the locations along the polarity inversion line where large flux ropes form and they agree in over 95% of cases with observed filament locations (Fig. 6).

What is clear from these impressive results is that that magnetic helicity transport over months and years is a fundamental part of coronal evolution. Thus, the coronal

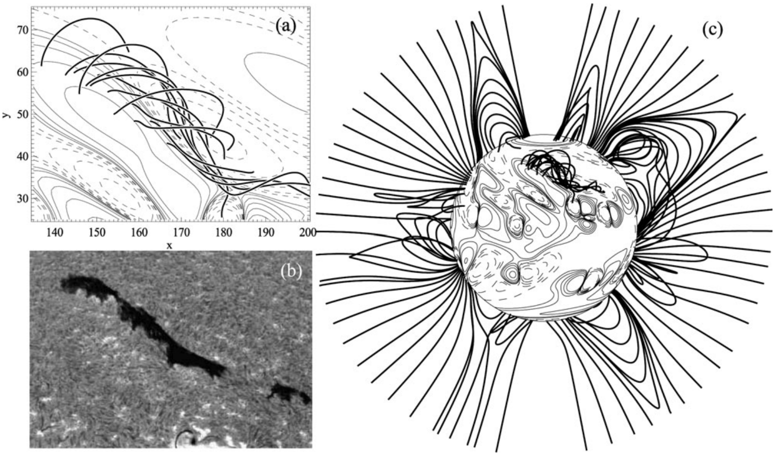


Figure 6. (a) A simulated nonlinear force-free field together with (b) an Hα image of a filament at the same location and (c) the global context in which the filament lies (Yeates *et al.* 2008).

magnetic field is certainly not potential and is very much a global system with rapid communication between its different parts.

5. What is the Cause of Fine Structure (Bubbles, Plumes, Threads and Tornadoes)?

Schmieder *et al.* (1984) first observed quantitatively the dynamic nature of prominences, by mapping the upflows and downflows. Later, Schmieder *et al.* (2010) demonstrated that apparent vertical motions in hedgerow prominences have a substantial component out of the plane of the sky, so they are inclined to the vertical. Here, Tom Berger (this volume) has demonstrated the dynamics in a series of dramatic movies from SDO and Hinode. He suggested that prominence bubbles are probably hot, and one idea is that they are caused by emerging flux (Dudík *et al.* 2012). This is suggestive, but more evidence is needed: the creation of a loop-like lower boundary could be a response to the evolution of fields in the filament channel and not necessarily flux emergence.

For plumes and threads, we are moving towards an explanation in terms of Rayleigh-Taylor instability, and the properties of plumes have been used to infer a plasma beta (Hillier *et al.* 2012). Including partial ionisation (Khomenko *et al.* 2013) has been a crucial step that is greatly welcomed (Fig. 7). Questions include: what is a physical explanation for the upflows and downflows and for the widths of threads? Can the observed properties of threads be quantified and then explained? Is the cause of threads a simple magnetic Rayleigh-Taylor instability or does it include resistive and radiative effects too?

David Orosco Suarez gave a promising observation of the magnetic field of threads, but it was puzzling that the field was uniform in threads. Stano Gunnar reviewed models for fine structure: he presented the possibility of tangled magnetic fields (van Ballegooijen and Cranmer 2010) and also of multi-thread models with a local dip and radiative transfer (Gunár *et al.* 2008).

Tornadoes are puzzling. Maria Martinez Gonzalez (this volume) used observations of Stokes parameters to deduce that a tornado is a rotating double helix with magnetic field 20–60 G. But what is the cause of tornadoes? How do they compare with barbs? Are tornadoes just barbs that are rotating?

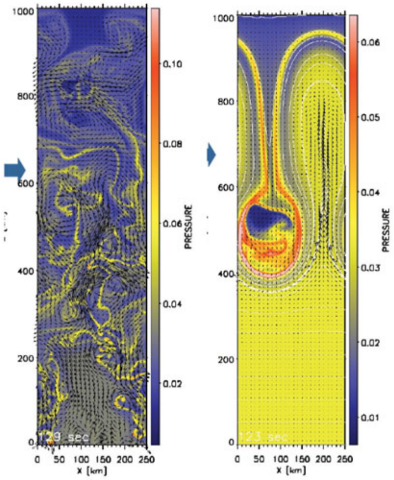


Figure 7. A numerical experiment to determine the effect of partial ionisation on magnetic Rayleigh-Taylor instability, showing contours of pressure (Khomenko *et al.* 2013).

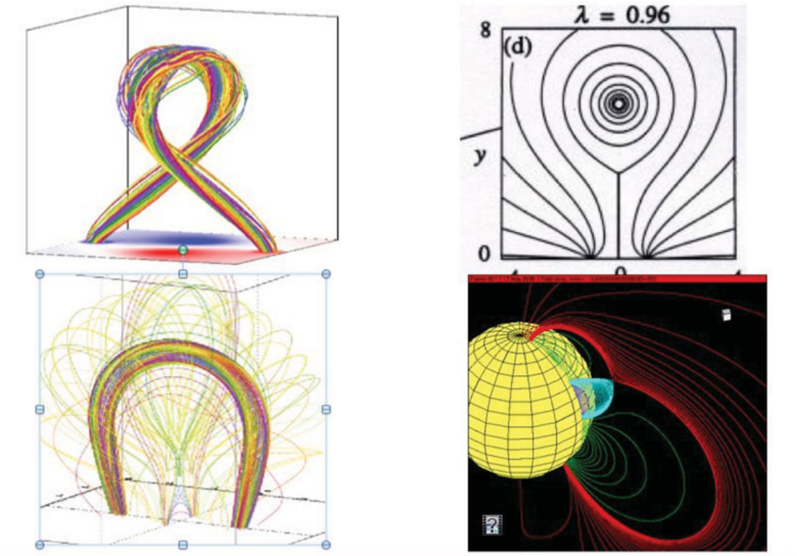


Figure 8. Four possible models for the eruption of coronal magnetic fields in a two-ribbon flare.

Masumi Shimojo (this volume) showed how prominence activation varies with the solar cycle. At present, even though the number of sunspots is half of the previous solar maximum, the number of prominence activations is almost as great. Also a butterfly diagram of prominence activity shows a rise in maximum latitude followed by a decline after solar maximum. At present, the activity is normal in the northern hemisphere but anomalous in the southern.

6. Why Do Prominences Erupt?

Previously, four mechanisms for prominence eruption had been suggested, namely, kink instability, nonequilibrium or catastrophe, torus instability and breakout (Fig. 8).

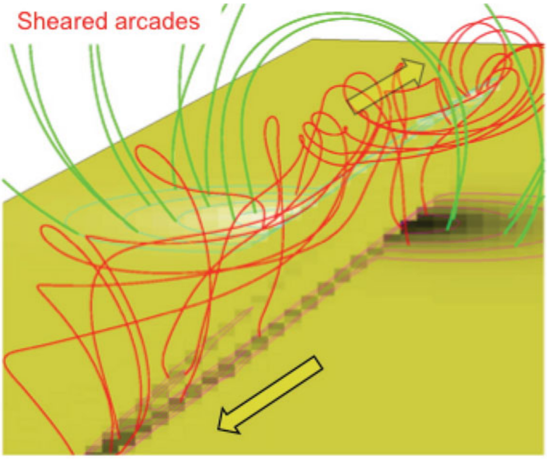


Figure 9. A sheared arcade model of a pre-eruptive magnetic configuration (Aulanier *et al.* 2006).

Kazunari Shibata (this volume) described his unified model (Shibata 1999) with plasmoid-induced reconnection and fractal current sheets (Nishizuka and Shibata 2013), triggered by emerging flux (Kusano *et al.* 2012).

Shibata also found 365 super flares (10^{35} erg) on solar-type stars. On the Sun this would be preceded by superspots and superprominences, so we don't need to start worrying until we see a superspot.

Guillaume Aulanier (this volume) discussed the physical processes for eruption and compared curved wire with MHD models, in which there is a balance between an upwards magnetic pressure force and a downwards magnetic tension force. Eruption could occur due to an increase in magnetic pressure or a decrease in tension due to reconnection or evolution. He concluded that eruption is usually due to torus instability or non equilibrium, and only rarely by breakout. Also, evolution to the critical point could occur in different ways.

One point to note is that torus instability is exactly the same as lateral kink instability, and another is that some flares have the reconnection occurring at separators (Longcope *et al.* 2007), some at null points (Masson *et al.* 2009) and some at quasi-separatrix layers (Mandrini *et al.* 1997; Aulanier *et al.* 2006).

7. Coronal Mass Ejections

Pascal Démoulin (this volume) described the properties of magnetic clouds, which are probably part of all interplanetary coronal mass ejections (ICME's). They show up as a rotation in the magnetic field and a low proton temperature in a one-dimensional spacecraft track. It is difficult to recognise flux ropes, but he showed how to find the axis and boundaries of a rope, and also how to calculate the density expansion. A flux rope can lose up to 50% of its flux by reconnection.

Noe Lugaz then showed how the whole CME can be imaged by Stereo and how complex the propagation of from Sun to Earth can be. Many properties can be determined, such as CME rotation, expansion, mass increase (by up to 50% by a snowplow effect), and interaction with other CME's. In all this, his numerical simulations are helping our understanding. Then Bob Wimmer-Schweingruber discussed the effects of CME's on space weather, starting with a wide-ranging history of ideas. He stressed that space weather matters throughout the heliosphere, since it affects outer planets and there can be a global reaction throughout the heliosphere to a CME. He showed that the radiation for a manned trip to Mars is of concern and stressed the need for multi-spacecraft observations in future. Also, Benoit Lavraud and Alisson Dal Lago showed how the geo-effectiveness of CMEs depends on the velocity and magnetic field direction, on their flux erosion during propagation, on the interaction with the Magnetosphere and on the accompanying shock waves.

The meeting concluded with a review of stellar prominences by Gaitee Hussain that showed how they can exist beyond the coronation radius and how they are occasionally ejected. Also, Maxim Khodachenko showed how stellar CME's affect planetary formation and how close Jupiters can be protected by a magnetosphere.

8. Final Comments

As an aside, some amusing comments during the meeting concerned the Huntsville express (Shi Tsan Wu), coronal *magnetic* eruptions (Tom Berger),"It is too good to be true" and "I am very conservative" (Jean-Claude Vial), "Here is a crazy idea" (Aad Van Ballegooijen, when describing his own work), "I am pretending to be Piet Martens" (Duncan Mackay) "or Judy Karpen" (Manuel Luna), "Twisted fields breed bunnies" (Sarah Gibson),"I like star trek and science fiction" (Guillaume Aulanier and Noe Lugaz), "I like superprominences" (Kazunari Shibata), "I like Hagar the Horrible" (Bob Wimmer Schweingruber) and "We need to cooperate with the Sun" (Pascal Démoulin).

Finally, the person whose kindly presence we have been remembering this week is Einar Tandberg-Hanssen, and the person whom we thank most of all for a fantastic conference is La Reine Brigitte.

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