Quiescent Prominence Dynamics: An Update on Hinode/SOT Discoveries

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Abstract. Hinode/SOT has revealed two new flow systems in quiescent prominences: large-scale (order 10 Mm) “bubbles” or “arches” that “inflate” below prominences to create dark cavities in the prominence, and small-scale (order 1 Mm) dark plumes that rise with constant velocity to heights of 10–20 Mm above their origin at the base of prominences. Both flow systems are highly dynamic with ascent speeds ranging from 1–30 km s$^{-1}$ and evidence in the small-scale plumes of Kelvin-Helmholtz instabilities and turbulent mixing. Neither flow system has been observed in active region prominences. Multi-instrument analysis of one typical cavity shows the column density to be at least a factor of 5 less than the overlying prominence plasma. We discuss the developing understanding of these flow systems in the context of a single formation mechanism: buoyancy instabilities in an emerging flux rope that interacts with the overlying prominence. Measurements of plume and bubble sizes and occurrence frequencies, combined with the column density finding, implies that these flows are a significant source of mass and magnetic flux for quiescent prominences and coronal cavities, respectively.

1. Introduction

We report here on our current understanding of the enigmatic quiescent prominence upflows first observed by Hinode/SOT over three years ago (Berger et al. 2008). Briefly, these upflows can be categorized into two classes: large-scale dark “bubbles” that can inflate into quiescent prominences to attain sizes of up to 50 Mm across the view plane, and small-scale dark plumes that rise with constant velocities of $\sim$15 km s$^{-1}$ from the base of prominences to heights of 10–20 Mm. Both flows have only been observed in quiescent prominences at the limb; no observations of these flows exist for active region prominences.

The significance of both flows lies primarily in offering a new source of mass to the overlying prominence and coronal cavity system. For many years it has been known that quiescent prominences, particularly the “hedgerow” or polar crown varieties, exhibit constant mass drainage in thin ($\sim$1 Mm or less) filamentary downflow streams. In spite of these apparently constant drainage flows, these prominences can maintain their basic shape for periods on the order of weeks, often only changing significantly following eruptions in coronal mass ejections (CMEs). A long-standing question is what
is the source, or sources, of prominence mass? What forces are acting to resupply a prominence with the mass that is continually lost to gravitational drainage?

Now with the direct observation of large and small-scale upflows in quiescent prominence systems, Hinode/SOT has revealed flows whose scale and frequency may help balance the constant downflows to resupply the prominence system with plasma. In addition, the small-scale upflows are observed to entrain existing prominence plasma thus directly countering the downflows. Finally, the large-scale bubbles are observed to destabilize and presumably release their mass at or above the top of the visible prominence, providing a direct supply of coronal cavity mass.

More intriguingly, these flows reveal a novel form of instability in the outer solar atmosphere. The dark turbulent upflow plumes in particular are unlike anything that has been previously observed at coronal heights, a region which, with the exception of flares, is usually thought of as dominated by magnetostatic physics. In the following sections we briefly review the dynamic properties of the new flows and put forward an emerging hypothesis that unifies the two phenomena under a single physical mechanism.

2. Large-scale Cavity Formation in Quiescent Prominences

Figure 1 shows the iconic example of a large-scale “bubble” formation beneath a quiescent prominence imaged by Hinode/SOT on 16-August-2007 (de Toma et al. 2010). The bubble is first clearly defined at about 16:20 UT when it is about 25 Mm across and 10 Mm high, measured from the approximate top level of the spicules. The dark bubble continues growing throughout the time series, eventually attaining a height of about 40 Mm before catastrophically destabilizing at approximately 19:10 UT. The collapse phase lasts until about 19:40 UT during which time the boundary “breaks” with the right portion of the bubble ascending above the top of the visible prominence (presumably into the coronal cavity above) while the left section falls inward. The mean ascent speed of the top of the bubble is approximately $1 \text{ km s}^{-1}$ during the early phase, accelerating to $20 \text{ km s}^{-1}$ just before the collapse. Approximately 90 minutes after the collapse, the bubble begins to reform in the same location, re-inflating to a height of 40 Mm at the end of the Hinode/SOT observing period. Note that in both the initial and re-inflated states, the cavity is highly asymmetric implying that it is not spherical.

A notable feature of this and many other prominence cavities is the sharp boundary between the overlying prominence and the dark cavity. The ubiquitous quiescent prominence downflows are seen to impinge on this boundary and deflect laterally, occasionally building up a bright “rim” on the bubble boundary. Some downflows of bright plasma appear to flow off of the rim either in-front-of or behind the bubble. The trajectories of these intrusion flows are not strictly vertical, with an oblique component that suggests they are being “deflected” out of the view plane by the bubble. Sometimes strong vertical downflows slightly deform the boundary of the cavity briefly when first impinging on it. Finally there are also occasional lateral shear flows along the boundary of the bubble, particularly in the early phase of formation. These lateral flows appear to push material upwards along the rim of the bubble at times, countering the downflows from above. The speeds of these lateral flows are 1–10 km s$^{-1}$ (Chae et al. 2008).

The 16-August-2007 event is the largest, clearest example of prominence cavity formation we have in the SOT database. However cavity formation below quiescent prominences is not uncommon. Figure 2 shows another large cavity formation event
Figure 1. Hinode/SOT Ca H filtergram series of a large quiescent prominence bubble observed on the west limb (N46) on 16-August-2007. Axes are labelled in Mm. The image has been rotated to put the limb roughly horizontal. The number in the upper left is the frame number in the series; UT times are in the lower right. The orange curves trace the boundary of the bubble; the yellow lines delineate the approximate top of the bubble. Note that in frames 250, 425, and 500 plasma can be seen cascading down in-front-of or behind the bubble.

Figure 2. Hinode/SOT Ca H filtergram series of a large quiescent prominence bubble observed on the west limb (N41) on 03-October-2007. Axes are labelled in Mm. The image has been rotated to put the limb (not shown) roughly horizontal. The number in the upper left is the frame number in the series; UT times are in the lower right. The orange curves trace the boundary of the bubble as it later develops into large plumes; the yellow lines delineate the approximate size of the perturbations as they grow into the large plumes. Note that the middle plume in frame 14 has pinched down and formed a mushroom cloud profile.
that was caught by SOT just at the point of destabilization on 03-October-2007. This cavity grows asymmetrically to a height of approximately 20 Mm before destabilizing and collapsing. In contrast to the mostly smooth contour of the 16-August-2007 cavity, this cavity shows the rapid growth of small perturbations that eventually form large plumes just prior to the collapse of the whole cavity. The initial perturbation wavelength is approximately 1.5 Mm and the average growth rate as measured from the frames shown in Fig. 2 is 1.1 km s\(^{-1}\). As in the 16-August-2007 event, the cavity immediately begins reforming after collapse, although in this case it does not attain its previous height or definition before observations cease. Also as in the 16-August-2007 event, the passage of this large cavity through the prominence does not destabilize the overall structure of the visible quiescent prominence.

While the Hinode/SOT results can establish the basic kinematic properties of these enigmatic prominence cavities, they cannot offer any insight into the thermodynamic or magnetic state in the bubbles. There is however one inference of cavity density made using a multi-instrument visible and EUV relative absorption study (Heinzel et al. 2008). In this measurement the column density of a small cavity in the 25-April-2007 prominence is shown to be approximately 20% of that of the overlying prominence plasma. Due to the possibility of contamination by foreground or background material in this observation, the factor of 5 reduction in density is a lower limit and the cavity may be evacuated to a greater degree. Thus we have a direct inference that prominence cavities are buoyant (i.e., less dense in a gravitational field) relative to the overlying prominence, a fact which is not surprising given that the dynamics of these flows appear similar in many respects to buoyant flow in other fluid dynamic systems (Turner 1973).

Further evidence of the commonality of these flows is that large dark cavities can be seen in many single prominence images, going back to the 19th century. But with only a single image, it is easy to mistake these cavities as static structures such as magnetic arches. Stellmacher and Wiehr (1973) report a cavity that rose through a prominence as a dynamic system, but this observation seems to have had little impact. More recently, de Toma et al. (2008) report two ascending dark cavity events in Mauna Loa Solar Observatory (MLSO) H\(\alpha\) observations.

3. Plume Formation and Prominence Cavities

The first discovery of the enigmatic small-scale dark upflows in quiescent prominences was made while examining Hinode/SOT data from the well-known 30-November-2006 prominence (Berger et al. 2008). At the time of discovery it was not appreciated that the dark area beneath the prominence was a significant factor in the formation of the plumes. Only after studying many more plume-forming prominences did it become clear that nearly all small-scale upflow systems originate from larger dark cavities below prominences. Figure 3 shows a closeup of the plumes forming above the particularly low-lying cavity in the 30-November-2006 prominence. This cavity never rose more than about 10 Mm above the limb over the entire 6 hours of observation, but it spawned many tens of plumes during this time.

Figure 4 shows another smaller cavity emerging into a quiescent prominence observed on 08-August-2007. On first emergence at about 19:49 UT the boundary of the cavity is smooth with a maximum height of about 2 Mm above the limb. The cavity ascent then stagnates 3 Mm above the limb while the cavity enlarges and darkens. Approximately 12 minutes after emergence the boundary of the cavity forms distinct
perturbations with a characteristic size of $< 1 \text{ Mm}$. These perturbations grow linearly in amplitude at $4.5 \text{ km s}^{-1}$ for two minutes. At about 20:02 UT one of the perturbations enlarges to a small plume. By 20:04 UT this “proto-plume” and two others have grown into clearly identifiable plumes that ascend into the prominence with speeds of about $10 \text{ km s}^{-1}$. Simultaneously the right side of the cavity begins to collapse to the left as it is entrained by the plume upflows. The whole cavity is then swept upwards, following the plume flows, and is no longer identifiable by 20:14 UT. Note the similarity of this sequence, but at $1/10$ the scale, to that shown in Fig. 2.

While the previous examples show very clearly the relation of plume upflows to instabilities on cavity boundaries, there are examples in the SOT database in which large plumes seem to rise directly from the spicules below a prominence, i.e. with no visible associated cavity. We believe these cases are either examples where the underlying cavity is obscured from sight by, e.g., the foreground spicules, or examples in which the “plume” is itself a smaller version of a buoyant cavity that rises directly into the prominence without stagnating or going unstable. Isolated plumes may also occur in the absence of the inverse density gradient provided by the cavities due to so-called “double-diffusive” buoyancy instabilities (e.g. Hughes and Weiss 1995).

Once formed, quiescent prominence plumes show remarkable similarities in their basic dynamics and appearance. Figure 5 shows a measurement of the trajectories and area growth rates of three plumes from the 30-November-2006 prominence. All of the plumes are characterized by an initial nearly linear displacement (constant velocity) with measurable deceleration in the final 25–50% of the plume lifetime. The mean speeds are 16.0, 15.6, and 16.7 km s$^{-1}$, respectively. The maximum speeds are between 25 and 29 km s$^{-1}$. In all cases, the deceleration coefficient is between 20.4–32.1 m s$^{-2}$ indicating that the plumes are far from ballistic. All plumes also show a linear growth
Figure 4. Hinode/SOT Hα filtergram series of a small quiescent prominence cavity observed on the East limb (N49) on 08-August-2007. Axes are labelled in Mm. The image has been rotated to put the limb roughly horizontal. The number in the upper left is the frame number in the series; UT times are in the lower right. The horizontal black lines trace the height of one perturbation that grows into an upflow plume.

Figure 5. (A) Small-scale plume displacement in Mm above the limb as a function of time for three representative plumes from the 30-November-2006 observations. (B) Plume area vs. time for the same three plumes. Error bars are 1-σ random errors in the measurements.
in area in the initial ascent phase. The linear fit to the area growth curve for Plume #3 in Panel B gives 0.021 Mm$^2$ s$^{-1}$ (21,000 km$^2$ s$^{-1}$). Table 3 summarizes quiescent prominence plume characteristics established by measurements on these and several more examples.

<table>
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<th>Characteristic</th>
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<td>6</td>
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<tr>
<td>Maximum height$^b$</td>
<td>Mm</td>
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<td>15</td>
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</tr>
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<td>17</td>
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<td>Absolute contrast$^c$</td>
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<td>Frequency of recurrence$^d$</td>
<td>s</td>
<td>200</td>
<td>500</td>
<td>600</td>
</tr>
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$^a$Measured across the widest extent of plume components.

$^b$Measured from the Ca H or H$\alpha$ limb.

$^c$Contrast of plumes is negative but is inverted here so that “minimum contrast” corresponds to the most difficult to distinguish. Note that for brevity we do not distinguish here between Ca H and H$\alpha$ contrast.

$^d$Measured for a single cavity beneath a prominence.

4. Conclusions

We speculate that the two novel quiescent prominence flows observed by Hinode/SOT are generated from the same mechanism, namely the emergence of a buoyant twisted flux rope beneath pre-existing quiescent prominences. The twist in the flux rope offers a natural mechanism to produce relatively sheared horizontal fields impinging from below onto the prominence. The density inversion is caused by the presence of the dense cool downflowing prominence plasma superposed on the lower density emergent flux rope. The magnetic fields act as an effective surface tension with the added complexity that the relative direction of the flux rope and prominence fields can act to either stabilize or destabilize perturbations to the boundary between the prominence and the flux rope (Chandrasekhar 1961). The large cavities can be understood as flux ropes for which the relative magnetic field strength and direction results in a critical wavelength longer than the characteristic perturbation lengths; thus all perturbations are stabilized and the cavity grows unimpeded into the prominence above. For lower shear angles and higher prominence field strengths, the flux rope is unable to ascend and the system has a critical wavelength less than the characteristic perturbations. These perturbations thus grow non-linearly to form classic Rayleigh-Taylor (RT) upflow plumes that mix the cavity mass and flux into the overlying prominence. This unified mechanism explains both mass supply for the prominence and the overlying coronal cavity as well. See Ryutova et al. (2012) for more details on the RT instability criteria.
We believe that the MLSO events described in de Toma et al. (2008) can be understood in this unified mechanism as small cavities or perhaps large plumes. Intriguingly, the MLSO events both show a bright core in the center of the bubble during the early ascent phase. This feature is absent in the Hinode/SOT observations to date. We believe that the much wider bandpass of the MLSO H\(\alpha\) filter relative to the Hinode/SOT H\(\alpha\) and Ca H filters (10 Å vs. 100 mÅ and 1 Å) captures continuum radiation that suggests a significant thermal impulse to the cavity. This is evidence that thermal buoyancy may act to enhance the density inversion between the flux rope and the overlying prominence thus biasing the Atwood number\(^1\) towards unity.

Finally we are compelled to note that low plasma-\(\beta\) conditions (presumably in the overlying prominence) do not inhibit the RT instability from occurring: the terrestrial ionospheric “Spread-F” and magnetospheric “bursty back flow” phenomena are both examples of RT instabilities that take place in very low-\(\beta\) plasmas. The magnetic field strength, direction, and thermal buoyancy in the flux rope relative to the overlying prominence determine the overall system stability criteria, not the plasma conditions in the prominence alone.

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**References**

Ryutova, R., et al. 2012, in these proceedings  

\(^1\)The Atwood number is defined as \(A = (\rho_2 - \rho_1) / (\rho_2 + \rho_1)\) where \(\rho_2 > \rho_1\) are the prominence and flux rope densities, respectively.