Hinode/SOT Observations of Quiescent Prominence Dynamics

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Abstract. Hinode/SOT observations of quiescent, or “Quiet Sun,” prominences (QSPs) have confirmed and extended several dynamic characteristics known from previous ground-based observations: filamentary downflow streams, large-scale vortex flows, long-period body oscillations, and counter-streaming flows have been seen in most QSPs to date. Beyond these known characteristics, we have discovered completely new dynamics in QSPs, primary among which are large-scale (up to 50 Mm diameter) “bubbles” that inflate below prominences, as well as dark turbulent plume upflows that intermittently traverse them to heights of 15 Mm or more above the chromospheric spicules. Here we briefly review the prominence dynamics seen in the SOT dataset and provide quantitative measures of some of their characteristics. In general we conclude that there is no such thing as a static prominence—all quiescent prominences are in constant motion, primarily in downflow streams along apparently vertical streamlines. The constant draining motion implies that there is no need for “suspension against gravity” of the prominence gas. Fully 3-D dynamic models that take into account non-steady prominence mass transport are required to advance our understanding of these enigmatic objects.

1. Introduction

Prominence research is among the oldest fields of solar physics, with the first systematic studies of prominences made during total solar eclipses in the late 19th century (Lockyer 1874). But weather, seeing, and instrumental issues such as scattering have made discoveries and measurements in this field difficult. “Movies,” or image time series, with sufficient spatial resolution, contrast, and stability to measure the dynamic modes in prominences have only rarely been obtained from ground-based telescopes. Notable successes in capturing short-duration movies at the Dunn Solar Telescope (Engvold 1981), the Big Bear Solar Observatory (Zirin 1976), and Meudon Observatory (Martres et al. 1981) demonstrate the complexity of prominence dynamics. These observations show that many QSPs consist of long vertical filaments, some of which are seen to be in downward motion. In addition, Liggett and Zirin (1984) reveal a clear case of a large-scale vortex rotation in a QSP, verifying earlier spectroscopic analyses by Öhman (1969). Indications of the oscillatory modes of prominences were also seen in early observations (Harvey 1969; Landman et al. 1977). Finally, counterstreaming flows along narrow threads were discovered in the doppler images of on-disk quiescent filaments (Zirker et al. 1998).

In November 2006, the Hinode/SOT instrument (Kosugi et al. 2007; Tsuneta et al. 2008) observed prominences above the limb of the Sun for the first time. It
was immediately apparent that the SOT was capable of providing a revolution-
ary break-through in the observation of prominences. SOT views prominences
in two spectral lines: the 656.3 nm Hα line and the 396.8 nm Ca II “H-line.”
The spatial resolutions in these lines are 230 km and 160 km, respectively (de-
termined by 2x2 pixel summing). Typical cadences for the movies are 15–30 s.
The spatial resolution, and more importantly the stability of resolution and low
scattering, afforded by the Hinode satellite allow 4–6 hour ~200 km resolution
movies of prominences to be routinely obtained.

The SOT prominence movies have verified all of the previously observed
dynamics (Berger et al. 2008). In addition two new dynamic modes have been
discovered: large scale “bubbles” that “inflate” below the base of QSPs, some-
times expanding up to 50 Mm in size before “popping”; and smaller, intermit-
tent, turbulent upflow plumes that appear dark as they rise to heights of 25 Mm
or more. We emphasize that neither mode has been observed in active region
filament or prominence observations. In the following sections of the paper we
catalog the main dynamics of QSPs, give some of the quantitative measurements,
and discuss the implications for the SOT discoveries on our understanding of
prominence physics. For brevity we omit discussion of oscillations and counter-
streaming flows.

2. Quiescent Prominence Dynamics: Previously Known Modes

2.1. Filamentary Downflows

When aligned approximately along a solar longitude, prominences are seen
nearly perpendicular to the line-of-sight (LOS) at the limb. Under these con-
ditions QSPs are seen to consist primarily of vertical filamentary downflow
streams, sometimes superimposed on a continuous “sheet” structure. Fig. 1
shows typical examples of downflow streams.

A key characteristic is that the flow speed is a relatively constant 10–
20 km s\(^{-1}\) after a brief initial acceleration. For a starting height of 20 Mm, this
speed is 10–20% of the expected free fall speed in solar gravity (~100 km s\(^{-1}\))
thus implying a drag force of some kind. An obvious candidate is a Lorentz force
due to the magnetic field lines permeating the prominence. Such a mechanism
has been proposed in a model by (Low and Petrie 2005) and recently endorsed in
observations by (Chae et al. 2008). However this mechanism has difficulties ex-
plaining the turbulent cascading of the streams, simultaneous initiation of closely
spaced streams, as well as merging of streams. Such characteristics would imply
a complex tangling of field lines with resultant reconnection dynamics that we
do not observe.

Alternatively, one can neglect ion-neutral collisions and carry out a simple
fluid dynamic drag force calculation. Based on the observed filament diameters,
typical QSP densities (Tandberg-Hanssen 1995), and assuming a unity drag co-
efficient, terminal velocities of 10–20 km s\(^{-1}\) result, close to the measured values.
Neglecting ion-neutral coupling may seem untenable, but Mercier and Heyvaerts
(1977) perform a detailed calculation of anisotropic resistivity in prominences
and come up with downflow speeds of less than 10 m s\(^{-1}\): effectively a diffu-
sion of neutrals three orders of magnitude below the observed speeds. Karpen
et al. (2006) simulate coronal condensations that traverse horizontal field lines
and eventually fall to the footpoints. However their model cannot produce extended condensation flows at chromospheric temperatures and the flow speeds are 50 km s\(^{-1}\) or higher. It is safe to say that we do not understand the nature of the filamentary downflows in prominences.

2.2. Vortex Flows

Like downflow streams, vortex flows are best seen when the LOS is perpendicular to the sheet. Since this arrangement is rare, we have only a few examples of vortex flows in the SOT database. The clearest is seen in the 30-Nov-2006 movie. In this case, the vortex is seen to initiate following a strong upflow that turns Northward/horizontal and rotates through an angle of about 900° (2.5 full rotations) at a rate of about 0.003 rad s\(^{-1}\). The diameter of the rotating region in the prominence is approximately 3 Mm implying a rotational velocity of 4.5 km s\(^{-1}\), about half the downflow stream velocities.

Vortex flows are difficult to reconcile with prominence models since the axis of rotation is apparently perpendicular to the sheet. Thus if the vortex is caused by magnetic field line rotation, those field lines are perpendicular to the QSP axis, in contradiction to models and measurements (Leroy et al. 1984; Bonmier et al. 1994; Casini et al. 2003) that show the field should be no more than 30° inclined to the longitudinal axis. In addition, a viable mechanism for causing
field line rotation at the observed rate does not exist. As in the case of the
downflows, we can imagine a purely hydrodynamic mechanism for the flow, but
this again ignores the partial ionization of the gas; how does a low-β partially
ionized plasma rotate in this manner, apparently ignoring the magnetic field?

3. Quiescent Prominence Dynamics: SOT Discoveries of New Dy-
namic Modes

3.1. Large-Scale Bubbles

Figure 2. Large-scale cavity formation in 16-August-2007 prominence at
the NW limb. The spectral band is the Ca II 396.8 nm H-line. Note the faint
emission within the cavity. This is plasma that has fallen from the bright
“arch” outlining the cavity, either in front of or behind the cavity and is
evidence that the cavity is actually a 3-D bubble.

Figure 2 shows an image from the 16-August-2007 observations of a large
QSP on the NW limb. These observations spanned 5 h during which time the
large dark cavity outlined in Fig. 2 grew from an initial height of about 3 Mm
to 30 Mm in height, almost to the top of the visible prominence. The cavity
then collapsed and immediately began to reform, reaching a height of about 20
Mm by the end of the observation. The speed of the top of the rising cavity was
approximately 9 km s\(^{-1}\) for the first 2.8 h with a rapid acceleration to about
70 km s\(^{-1}\) just prior to the collapse.

Photographs from early prominence observations often show large cavities
as well, however in a single image it is impossible to see that they are actually
highly dynamic. Stellmacher and Wiehr (1973) report a single case of a rising
cavity with a projected speed of about 12 km s\(^{-1}\), close to what we measure in the
16-August-2007 event. So this dynamic may not be strictly an SOT discovery.
More recently, de Toma et al. (2008) have seen two cases of rising cavities in
Mauna Loa Solar Observatory wide-band H\(\alpha\) sequences (see also DeToma et al.
in these proceedings). But the extended observing times and uniform quality of the SOT movies have clearly pointed out that this is a common and highly intriguing dynamic mode of QSPs.

The arches above the cavities usually show brightness enhancement over the prominence sheet implying concentration of mass. Also, in most cases, the ubiquitous downflow streams terminate on the arches. In fact, in data taken on 29-September-2008, we observe a downflow stream apparently “bouncing” off of a cavity, as if it hit a solid wall 10 Mm above the chromosphere!

Plasma in downflow streams is also often seen to apparently deflect in front or behind the cavity, as in Fig. 2. For this reason we believe these structures to be three-dimensional “bubbles.” The only viable mechanism for large-scale structures that can so effectively stop or deflect the downflow streams is a strong magnetic field. If we extrapolate the arch structure at its maximum height in the 16-Aug-2007 observation down to the photosphere, the resulting “diameter” is approximately 45 Mm, somewhat larger than the typical supergranular cell diameter. Thus a primary question is what magnetic field process can create coherent 3-D structures spanning supergranular scales in the quiet Sun?

3.2. Turbulent Upflows

![6. Uplow Plumes](image)

**Figure 3.** Typical upflow characteristics and a representative upflow from the 30-November-2006 Ca II H-line dataset. This upflow shows a classic “dual vortex head” formation commonly seen in buoyancy-driven flows.

Finally, we examine the one dynamic mode that has never been previously reported: small-scale turbulent upflows. Figure 3 shows a representative ex-
ample of a turbulent upflow in the 30-November-2006 dataset. The summary characteristics also show a Reynolds number estimate based on typical QSP density values (Tandberg-Hanssen 1995). The estimated Re is within the transitional range, far from laminar flow. However the estimated plasma-$\beta$ is only 0.1. Again it is difficult to understand how a low-$\beta$ plasma can exhibit such turbulent flow.

Figure 4 shows a rather large upflow seen in the 8-August-2007 SOT observations. This flow became visible as a cavity about 300 km in diameter at a height of 5 Mm above the photospheric limb, i.e. just above the spicules. It then develops a highly turbulent profile, eventually splitting into two main head structures, as it flows to a maximum height of 16 Mm in about 15 min with an average speed of 16 km s$^{-1}$. At its maximum height, the dark structure slowly brightens to the ambient emission level of the prominence.

Figure 4. A large and highly turbulent upflow from the 08-August-2007 H$\alpha$ line-center dataset.

The distinguishing features of these flows are that they are always dark in H$\alpha$ or Ca II H-line images, they are always turbulent, they rise with almost constant velocity, and they terminate somewhere in the main body of the prominence by brightening to the ambient emission levels. Unlike the relatively constant and ubiquitous downflow streams, the upflows are intermittent and do not occur at all locations or at all times below any given QSP. The small size and
intermittent occurrence are what probably hid these features from ground-based observers.

4. Discussion

Of the dynamics discussed here, the two latter modes are by far the most novel and intriguing. The common characteristics in the bubbles and the turbulent upflows is that they are dark and they rise through the existing prominence gas at relatively constant speeds. Another observation that bears emphasizing: there are several cases in which turbulent upflows originate from the tops of large-scale bubbles (e.g. 8-Aug-2007 20:00 UT). This usually results in the bubble partially or totally collapsing, as if the material escaping in the dark upflows is deflating the bubble. An additional and important characteristic of both dynamics is their intermittency. Any theory explaining these dynamics must explain why they only happen occasionally and only at some locations below prominences.

We suggest that both the large-scale bubbles and the small-scale upflows are generated by a common mechanism: cancellation of magnetic flux at the underlying polarity inversion line (PIL). The cancellation results in twisted field lines, heated due to reconnection, with both thermal and magnetic buoyancy. The heating also causes the regions to be dark in visible-light spectral lines due to atomic level population redistribution. The resulting “plasmoid” is constrained from above by the existing field topology of the coronal cavity, of which the visible prominence is just the lowermost part (Low 1999). Subsequent cancellations add more field and heat to the plasmoid. If the overlying field is weak, the buoyancy of the concentration rapidly exceeds the restraining tension force and a small-scale turbulent upflow results. If the overlying field is stronger, the plasmoid cannot release and it continues to “inflate” thus forming one of the large bubbles. Finally, the bubble buoyancy reaches a critical point and it breaks the restraint of the overlying field during the burst phase.

Whatever the cause of these phenomena, it is clear that they both supply mass and energy to the prominence/cavity system. The small-scale upflows supply mass to the prominence since they stop rising within 50 Mm of the surface and are observed to “fade” into the background emission. Meanwhile, the large bubbles supply mass (and flux) to the coronal cavity since they are often observed to rise through the entire prominence before breaking. Inclusion of these new mass sources, as well as the primary mass sink of the draining filamentary downflows, into full 3-D models of the coronal cavity/prominence system is needed in order to advance our understanding of both prominence structure and CME initiation.

In this brief review we have shown the capability of the Hinode/SOT instrument to study QSPs with a level of detail never before achieved. Although most of the dynamics discussed here have been briefly seen in ground-based observations, the clarity and stability afforded by an orbital space platform have resulted in major advances in our knowledge of prominence structure and dynamics. Thanks to the Hinode/SOT, arguments against the utility of flying visible light solar telescopes in space have been put permanently to rest. A useful subsequent mission to Hinode/SOT would be a high resolution imaging spectropolarimeter capable of Hanle and Zeeman measurements of prominence
and coronal magnetic fields, again following on the tantalizing preliminary results from the ground-based research of the past 30 years.

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