1. INTRODUCTION

Quiescent prominences, or filaments, are dynamic formations of relatively cool and dense plasma ($T \sim 10^4$ K, $n_e \sim 10^{11}$ cm$^{-3}$) extending into the much hotter and rarefied corona ($T \sim 10^6$ K, $n_e \sim 10^8$ cm$^{-3}$) over magnetic polarity boundaries far from active regions (Martin 1998; Tandberg-Hanssen 2012; Priest et al. 1978; Schmieder et al. 1984). In the “polar crown” regions they are frequently observed in so-called coronal cavities, dark elliptical structures seen during eclipses or in extreme ultraviolet (EUV) and X-ray images of the corona (Kucera et al. 2012; Reeves et al. 2012; Schmit & Gibson 2011; Habbal et al. 2010; Fuller & Gibson 2009). In situ condensation of hot plasma from the coronal cavity, in support of our previously proposed process of magnetothermal convection in coronal magnetic flux ropes.

Key words: Sun: chromosphere – Sun: coronal mass ejections (CMEs) – Sun: filaments, prominences

Online-only material: animations, color figures
Figure 1. Time sequence of SDO/AIA images in the 171 Å (yellow) and 304 Å (red) channels. Note the disappearance of the prominence from the cavity, (a)–(c), the appearance of a bright emission cloud, (d)–(e), and the formation and growth of a new prominence, (f)–(i). See also movies 1a and 1b, 304 Å overlaid on 171 Å and 211 Å, respectively.

(Animations (1a and 1b) and a color version of this figure are available in the online journal.)

Following the disappearance, the cavity region near the limb remains prominence-free for some 5–6 hr. Meanwhile, a “cloud” of hot plasma gradually accumulates near the core of the cavity. The cloud has the highest contrast against the background in the FeIX 171 Å channel and develops into its brightest apparition by April 28 01:28 UT. At about April 27 22:00 UT there is an initial appearance of 304 Å emission at the lower edge of the cloud. Figures 1(d)–(f) illustrate this initial cloud formation and prominence appearance sequence.

Figures 1(g)–(i) show that the 304 Å emission continues to expand in both height and width over the next several hours. Simultaneously, the size of the 171 Å emission cloud decreases markedly. By April 28 04:00 UT the 171 Å emission is confined largely to the region surrounding the growing prominence. Thin threads of 171 Å emission can be seen curving outward and upward from the prominence at this time. Such prominence “horns” have been observed in both prior AIA data (Régnier et al. 2011) as well as Solar and Heliospheric Observatory data (Vourlidas et al. 2012; Plunkett et al. 2000). In the final period of the observation, the 171 Å emission is confined to a very narrow “Prominence Corona Transition Region” (PCTR) sheath (Parenti & Vial 2007) with some residual projections upward into the cavity. At this point, the coronal cavity is again well defined in the 211 Å channel. The total time from initial appearance in the 304 Å channel to the fully extended prominence in panel (i) is approximately 18 hr.

3. MULTISPECTRAL ANALYSIS OF THE COOLING CLOUD

Figure 2 shows a subset of the temporal sequence discussed above in the FeXII 193 Å and 171 Å channels. The subset begins at April 27 10:55 UT when there was no prominence visible in the 304 Å channel, and shows a largely featureless, barely visible, coronal cavity in the 193 Å channel while the center
Figure 2. Comparison of coronal cavity emission cloud appearance in the 193 Å (left) and 171 Å (right) channels over time. Note that the emission cloud fades in the 193 Å channel, (b)–(c), while it brightens in the 171 Å channel, (f)–(g). See also movie 2. (An animation and a color version of this figure are available in the online journal.)

of the cavity is well defined in the 171 Å channel. The second row of Figure 2 shows the clearly developed cloud structure in both channels. By April 28 04:00 UT the cloud has decreased in contrast in the 193 Å channel while remaining bright and high contrast in the 171 Å channel (third row of Figure 2). The fourth row shows that the prominence has fully formed by April 28 16:40 UT. Absorption of the 193 Å emission by both the prominence and some of the residual horn structure (see Figure 1(h)) is evident.

Figure 3 shows the emission in the 211, 193, 171, and 304 Å channels averaged over slices taken from the vertical box that encloses the central region of the cavity shown in panel (a). Panels (b)–(e) show the resulting “time slices” in each channel. Emission in the 211 Å channel is spatially concentrated and brightest (relative to the reference frame) at April 27 13:30 UT. Emission in the 193 Å channel is spatially most compact and brightest several hours later at 20:45 UT. Similarly, the 171 Å emission is compact and brightest at April 28 01:28 UT. Finally, the prominence has its brightest, most compact 304 Å emission at April 28 07:10 UT. Note that the height of maximum emission steadily decreases with time and decreasing wavelength (and temperature) in the 211, 193, and 171 Å sequence. The first appearance of the 304 Å prominence emission occurs only after the cloud has descended to a height of approximately 75 Mm in the 171 Å channel.

4. FILTER RATIO TEMPERATURE ANALYSIS

Given the wide spectral passbands of AIA, a detailed determination of the plasma temperature and density along the lines of Heinzel et al. (2008) is not possible. However we can use the known AIA instrument response functions to calculate a temperature range for the emitting cloud structure as a function of time. While this method implicitly assumes an isothermal temperature distribution for the plasma (which is unlikely to be
Figure 3. Time-slice analysis of the emission cloud. (a) 211 Å channel image taken when the prominence has fully formed. The cavity outline is well visible as is the absorption due to the prominence. The vertical dotted box indicates the region over which vertical columns of pixels are averaged to create time-slice images in the 211, 193, 171, and 304 Å channels. The constant height dotted box ($h = 144''$ above the limb) is used in the time slice of Figure 5. White “+”s mark the lower left corners of the time slices. (b)–(e): base ratios with the reference image time for each panel indicated by a small circle. Color bars indicate the intensity ratio ranges. Black “×”s mark the locations and times of peak emission in each panel. The yellow curves plot relative emission (arbitrarily scaled) along the horizontal dashed lines that traverse the cavity at heights corresponding to the peak emission in each channel. The white contour in all panels shows the outline of the prominence in the 304 Å channel. The peak temperature of emission in each channel is indicated next to the wavelength identifier in units of $10^6$ K (MK).

(A color version of this figure is available in the online journal.)
valid in a complex coronal cavity, e.g., Kucera et al. 2012), it has the advantage of having no adjustable parameters and is not an ill-posed inversion problem.

Figure 4(a) shows the measured temperature response curves of the AIA telescopes from aia_get_response.pro. Taking the ratios 171/211, 193/211, 211/335 gives the set of curves shown in Figures 4(b)–(d). The emission of the cloud in each channel is measured by averaging the emission of 3×3 “pixel” samples around the X-marks shown at specific times in Figures 3(b)–(d). The ratios are then computed and plotted on Figures 4(b)–(d) as the dotted horizontal lines.

We measured all 10 ratios from the set {131, 171, 193, 211, 335} Å at each of the specific times above. The temperatures at the intersections of these 10 ratios with the response curves are shown as short vertical bars on the axes of Figures 4(e)–(g). These measurements are binned in temperature to create histograms of inferred temperatures, showing that there are two most likely solutions around log $T \sim$ 5.35 and 6.2 K. The peak around log $T \sim$ 6.2 K shows a larger degree of clustering than the lower temperature peak implying that it is the more likely solution. In addition, this peak shows a trend toward cooler temperature over the three time steps sampled in the data set. In particular, the mode of the peaks are log $T \sim$ 6.25, 6.15, and 6.15 K for the times April 27 13:30 UT, April 27 20:45 UT, and April 28 01:28 UT, respectively. The latter peak, while having the same mode as the previous time, shows a pronounced tail toward the cooler temperature range. In contrast, the log $T \sim$ 5.35 K peak does not show such a consistent trend.

Taken together, the filter ratio analysis implies that the initial temperature of the emission cloud is log $T \sim$ 6.25 K with a cooling trend over time. Emission ultimately appears in the 304 Å channel, implying a very definite cooling trend, however this filter cannot be used in the foregoing filter ratio analysis because the plasma is optically thick in He II, violating the optically thin assumption in the response curves of Figure 4.

5. PROMINENCE MASS AND CAVITY CONTRAST COMPARISON

Figure 5 shows a contrast analysis of the coronal cavity in the 211 Å channel along with a mass estimate in the quiescent prominence. Cavity contrast is calculated by examining the average emission in a time slice of constant height pixels (dotted outline in Figure 3(a)). Figure 5(a) shows the time slice and reveals that the core of the cavity darkens significantly beginning around April 27 16:00 UT. This is several hours after the peak 211 Å emission of the cooling cloud, but roughly coincides with the rise to maximum emission in the 193 Å cloud, as shown in Figure 3. As the cloud emission intensifies in the cooler channels, the cavity darkens further until by about April 28 16:00 UT, the cavity achieves maximum darkness in the core. Although cavity contrast is a strong function of view angle and hence can be influenced by solar rotation, at the heliographic latitude of the cavity (N68), the rotation is only 6° over the 12 hr during which the cavity contrast changes significantly, too little to explain the observed contrast change. We note also that the darkest region of cavity extends over a larger region than the prominence absorption.

We estimate the prominence mass as the “plane-of-sky” (POS) mass, calculated by measuring the area of emission detected in the 304 Å channel and assuming that the prominence is a uniform thickness slab in the POS. This method grossly underestimates the true mass of the prominence since most prominences have significant longitudinal extent. Nevertheless, the method allows an analysis of prominence mass over time at a zero-order level of detail; changes in the assumed geometry of the prominence will alter only the absolute mass number and not the shape of the temporal curve. Here we assume a typical
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Figure 5. Coronal cavity contrast and prominence mass cycle. (a) Time-slice image in the 211 Å channel formed from the average of all constant height pixels in the dotted outline in Figure 3(a). The thick white outline shows the coronal cavity as it reaches its highest contrast. The darkest central core of the cavity appears at a position of 340″, offset by approximately 40″ from the location of the 304 Å prominence indicated by the thin white contours. (b) 304 Å “plane-of-sky” mass of the prominence as a function over the same time period. The POS mass increases roughly simultaneously with the increase in coronal cavity contrast. (A color version of this figure is available in the online journal.)

Prominence density of \( n_e = 8 \times 10^9 \text{ cm}^{-3} \) (Labrosse et al. 2010) or \( \rho = 1.3 \times 10^{-14} \text{ g cm}^{-3} \), and a thickness of 10″ (7300 km) to arrive at the numbers shown in Figure 5(b).

The plot shows that the POS mass of the prominence steadily decreases at an average rate of approximately \( 2.4 \times 10^{13} \text{ g hr}^{-1} \) from 00:00 UT to 12:00 UT on April 27. Beginning at about 22:00 UT, the new prominence forms initially at about the same rate. However the rate decreases after April 28 3:00 UT and is highly variable thereafter. Note that the onset of rapid coronal cavity darkening in the 211 Å channel corresponds well with the onset of prominence appearance in the 304 Å channel and that the cavity core increases in darkness as the prominence continues to accumulate mass (see Movie 1b). Since coronal cavity core contrast is largely a function of plasma density relative to the surrounding corona (Fuller & Gibson 2009), we interpret the darkening of the cavity core to indicate a loss of plasma from the region.

6. SUMMARY AND DISCUSSION

We have analyzed observations of the dynamic formation of a quiescent polar crown prominence in a coronal cavity. The sequence of events is summarized as follows.

1. A pre-existing prominence slowly disappears due mostly to drainage and lateral transport of plasma (Figure 1).
2. A bright emission cloud forms in the upper regions of the coronal cavity (Figures 1 and 2).
3. The cloud descends toward the lower region of the cavity while sequentially becoming brighter in the 211, 193, and 171 Å channels (Figure 3).
4. A new prominence appears in the 304 Å channel and rapidly grows in both vertical and horizontal extent (Figures 1 and 3).
5. The coronal cavity core above the prominence grows darker in the 211 Å channel as the 304 Å prominence grows (Figure 5).
6. When the prominence reaches its maximum size after approximately 18 hr of growth, the emission cloud in the cavity is completely gone (Figure 1).

Taken together, these observations are consistent with the hypothesis that the quiescent prominence has formed via condensation from hotter plasma contained in the core of the coronal cavity. We interpret the EUV emission sequences in Figures 1–3 as evidence of radiative cooling and descent of the hot plasma in the coronal cavity core, first appearing bright in the hotter 211 Å channel with a peak temperature of formation of \( \log T_{\text{max}} \sim 6.2 \text{ K} \), followed by a shift to emission in the 193 Å channel (\( \log T_{\text{max}} \sim 6.1 \text{ K} \)), followed by another shift to emission in the 171 Å channel (\( \log T_{\text{max}} \sim 5.8 \text{ K} \)), and finally appearing in the “chromospheric” 304 Å channel (\( \log T_{\text{max}} \sim 4.8 \text{ K} \)).

The profile of the hotter filter ratio histogram widens toward cooler temperatures over time (Figure 4(g)), further supporting our interpretation that the observed plasma radiatively cools to condense into the prominence. The drop in the height of the cloud further supports this hypothesis. Radiative cooling is
proportional to $n_2^2$ at corona temperatures and increases with decreasing temperature in the log $T \sim 5\rightarrow 7$ K range. Therefore, a “runaway thermal instability” is possible in which the plasma cools increasingly rapidly as it becomes denser and cooler (Low et al. 2012a). The increased density of the cloud naturally results in higher gravitational force countering the local Lorentz force of the cavity magnetic field. Thus, the descent of the cloud is consistent with radiative cooling and condensation in a weakly magnetized environment as the plasma seeks a new equilibrium height, possibly through resistive reconnection (Low et al. 2012b). As the prominence gains mass at the expense of the hot cloud, the coronal cavity simultaneously becomes more sharply defined in the 211 Å channel due to mass loss from the core region.

The observations shown here imply the possibility of in situ formation of prominences in coronal cavities. Given the large density disparity, Tandberg-Hanssen (1995) estimated that the entire coronal mass could only support such condensation for a few large prominences. However, this concern was based on the implicit assumption that prominences are magnetostatic suspensions of a fixed amount of plasma. But as shown by recent SDO/AIA and Hinode/SOT observations, quiescent prominences are in constant motion via drainage downflows (Liu et al. 2012; Haerendel & Berger 2011; Chae et al. 2008) and re-supply of mass through various mechanisms (e.g., Berger et al. 2008, 2010, 2011; Li et al. 2012; Su et al. 2012). Liu et al. (2012) estimated the mass loss in prominence downflows to be $10^{15}$ g day$^{-1}$ or roughly the equivalent of a typical CME mass.

Thus, the mass in a prominence changes significantly with time and is not directly related to the mass in the global corona in a simple manner. Mass balance in prominences appears to be a cyclic process in which the mass transported into the coronal cavity determines how much can eventually condense to form prominences. Similar cyclic processes have been proposed for the quiet-Sun coronal mass balance (McIntosh et al. 2012; Antolin & Rouppe van der Voort 2012; Marsch et al. 2008) and coronal rain condensation (Landi et al. 2009; Schrijver 2001).

Observations at the limb necessarily integrate along heliographic longitude. Thus, it is possible that the prominence that disappears is not at the same longitude as the new prominence that forms or that the cloud and the new prominence are a line-of-sight coincidence. But the fact that the shrinkage of the cloud (darkening of the cavity), the descent of the cloud, the formation of prominence “horns,” and the eventual formation of a PCTR sheath are all synchronized with the growth of the prominence in the 304 Å channel argue against a line-of-sight coincidence. We note that the hot cloud itself exhibits no significant flows, other than its slow radial descent, during the condensation process. Thus, it is unlikely that we are confusing in situ condensation with flow-based formation mechanisms such as flows between disparate magnetic footpoints (e.g., Xia et al. 2012; Luna et al. 2012; Karpen & Antiochos 2008; Antiochos et al. 1999).

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