SDO/AIA Observations of Coronal Condensation in Prominences as Return Flows of the Chromosphere-Corona Mass Cycle

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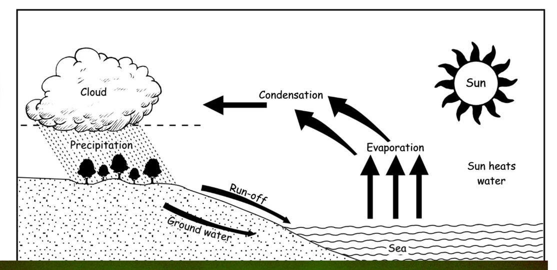
(Liu, Berger, Low 2012 ApJL; Low, Berger, Casini, & Liu, 2012 ApJ in press)



§1. Introduction. It has recently been proposed that prominences are manifestations of a magneto-thermal convection process that involves ever-present dynamic descents of cool material threads and upflows of hot plasma (Berger et al. 2011 *Nature*). On global scales, prominences may play an important role as the return flows of the chromosphere-corona mass cycle, in which hot mass is originally transported upward by spicules and/or other mechanisms. A critical step in this cycle is the condensation of million-degree coronal plasma into T<10,000 K prominence material by radiative cooling instability (modeled by, e.g., Karpen/Luna/Antiochos/Klimchuk, C. Xia/PF Chen et al.). However, direct observation of coronal condensation has been difficult in the past, a situation recently changed.

§2. Condensation in Funnel Prominences (Liu, Berger, Low 2012)**.** We present here the first example observed with SDO/AIA, in which hours of gradual cooling through multiple EUV channels (from 2 MK to 80,000 K) in large-scale loops leads to eventual condensation at magnetic dips, where we find possible evidence of magnetic reconnection and subsequent downflows. A moderate-size prominence of 10^{14} gram is then formed. Its mass is not static but maintained by a continual supply through condensation at a high rate of 10^{10} gram/s against a comparable drainage through numerous vertical threads at less than free-fall speeds. Most of the total condensation of 10^{15} gram, comparable to a CME mass and an order of magnitude more than the instantaneous mass of the prominence itself, is drained in merely one day. These new observations show that a macroscopically quiescent prominence is microscopically dynamic, involving the passage of a significant mass that bears important implications for the chromosphere-corona mass cycle. This interpretation is supported by the recent theoretical development on spontaneous formation of current sheets and cool condensations (Low, Berger, Casini, & Liu, 2012).

§3. First Observation of Prominence Formation in Coronal Cavity.

1. Introduction

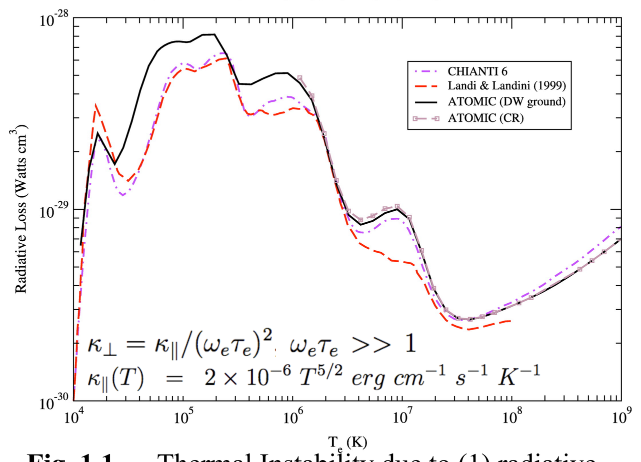


Fig. 1.1 — Thermal Instability due to (1) radiative losses from coronal plasma (Colgan et al. 2008 ApJ); (2) thermal conduction suppressed across magnetic field lines, making magnetic fields perfect insulators.

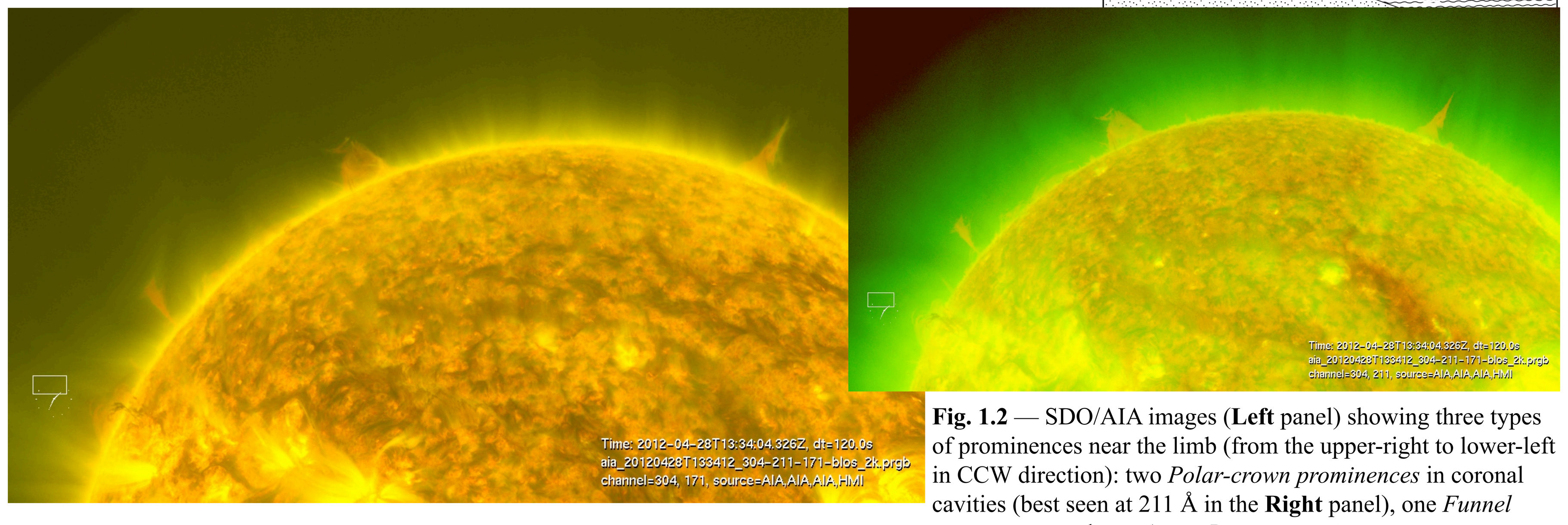


Fig. 1.2 — SDO/AIA images (**Left** panel) showing three types of prominences near the limb (from the upper-right to lower-left in CCW direction): two *Polar-crown prominences* in coronal cavities (best seen at 211 Å in the **Right** panel), one *Funnel prominence*, and one *Active Region prominence*.

2. Condensation in Funnel Prominences

2.1 Prominence of Nov-26-2010 in Trans-equatorial Loops

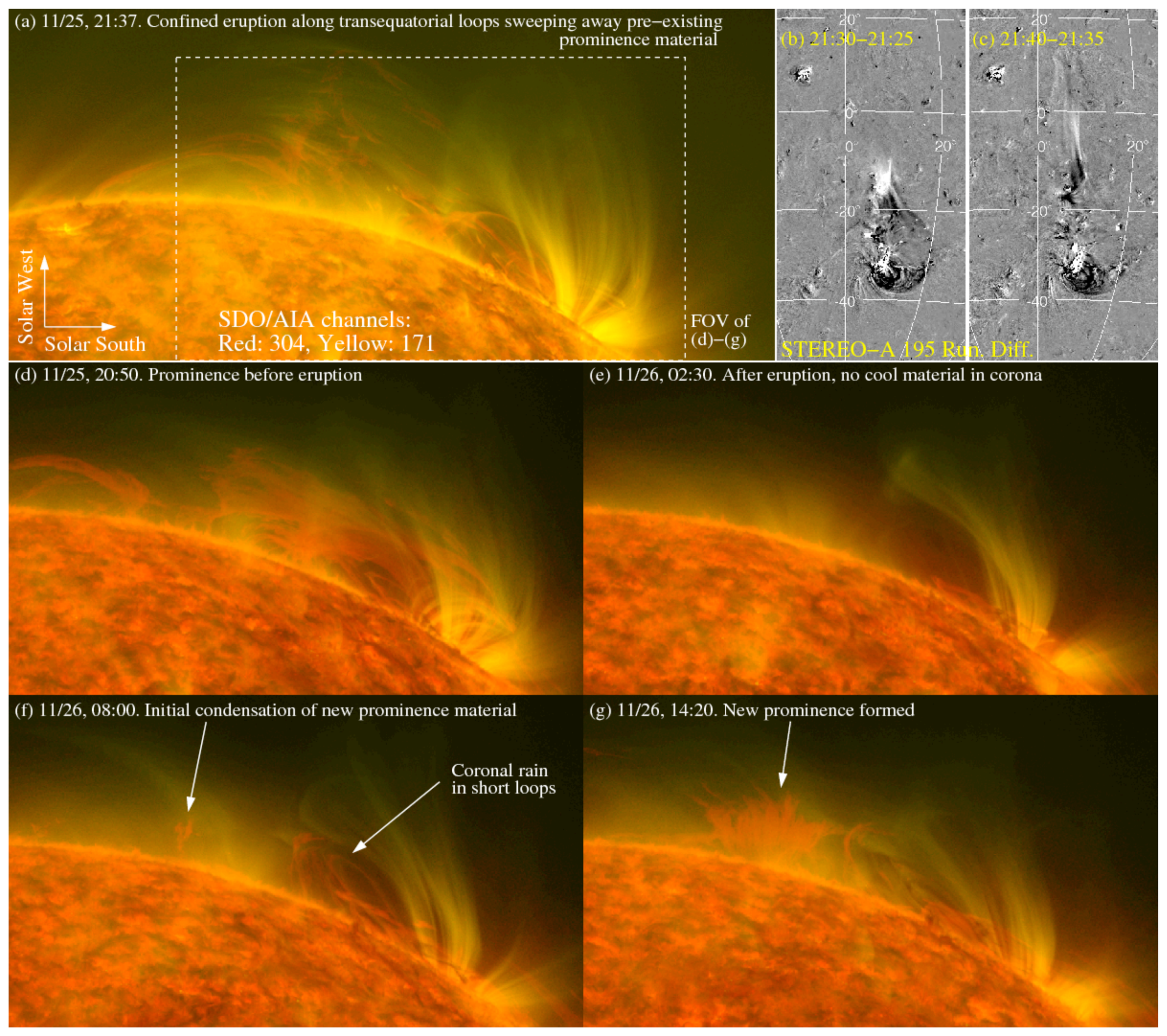


Fig. 2.1— Composite AIA 304 (red) and 171 Å (yellow) images showing coronal condensation forming a prominence after a confined eruption that sweeps away the existing prominence material and is channeled by trans-equatorial loops to land on the other hemisphere.

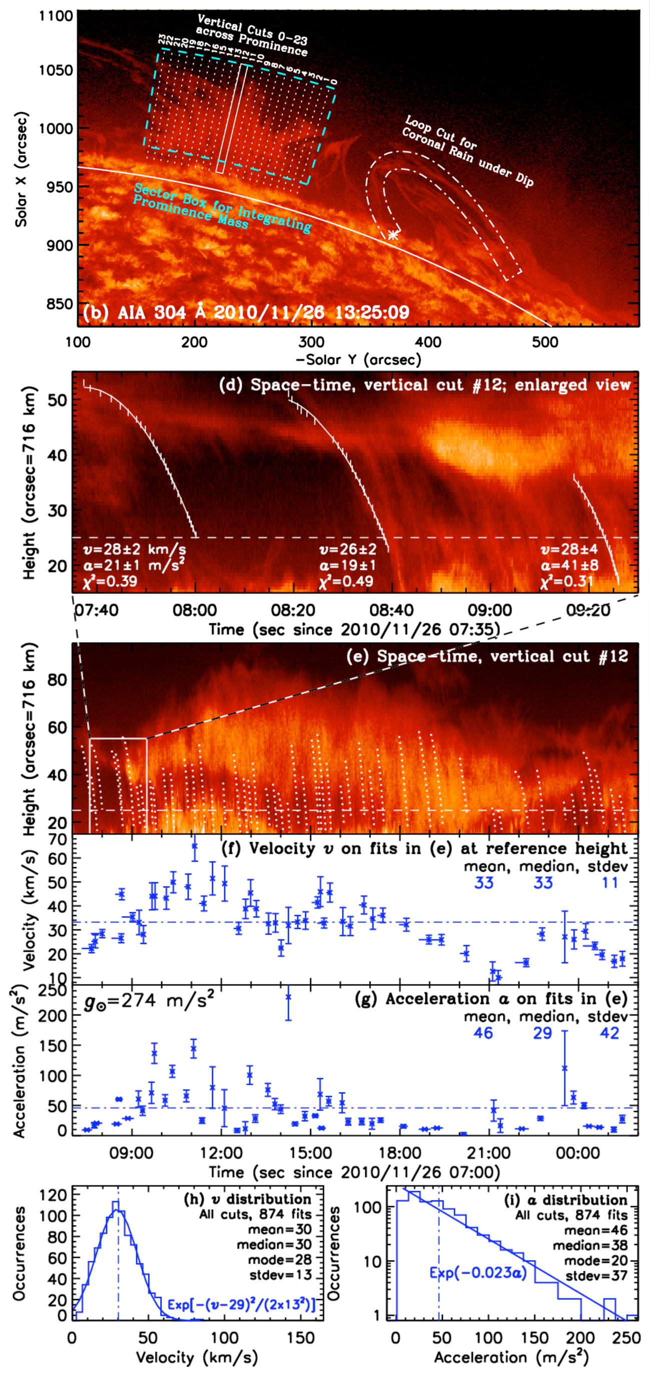


Fig. 2.2— **Top**: AIA 304 Å image showing a sector for integrating prominence mass in Fig. 2.5(a) and narrow vertical cuts for obtaining space-time plots in **(d)** & **(e)**, where white lines are parabolic fits to drainage trajectories for measuring velocity **(f)** and acceleration **(g)**, with their histograms at the bottom.

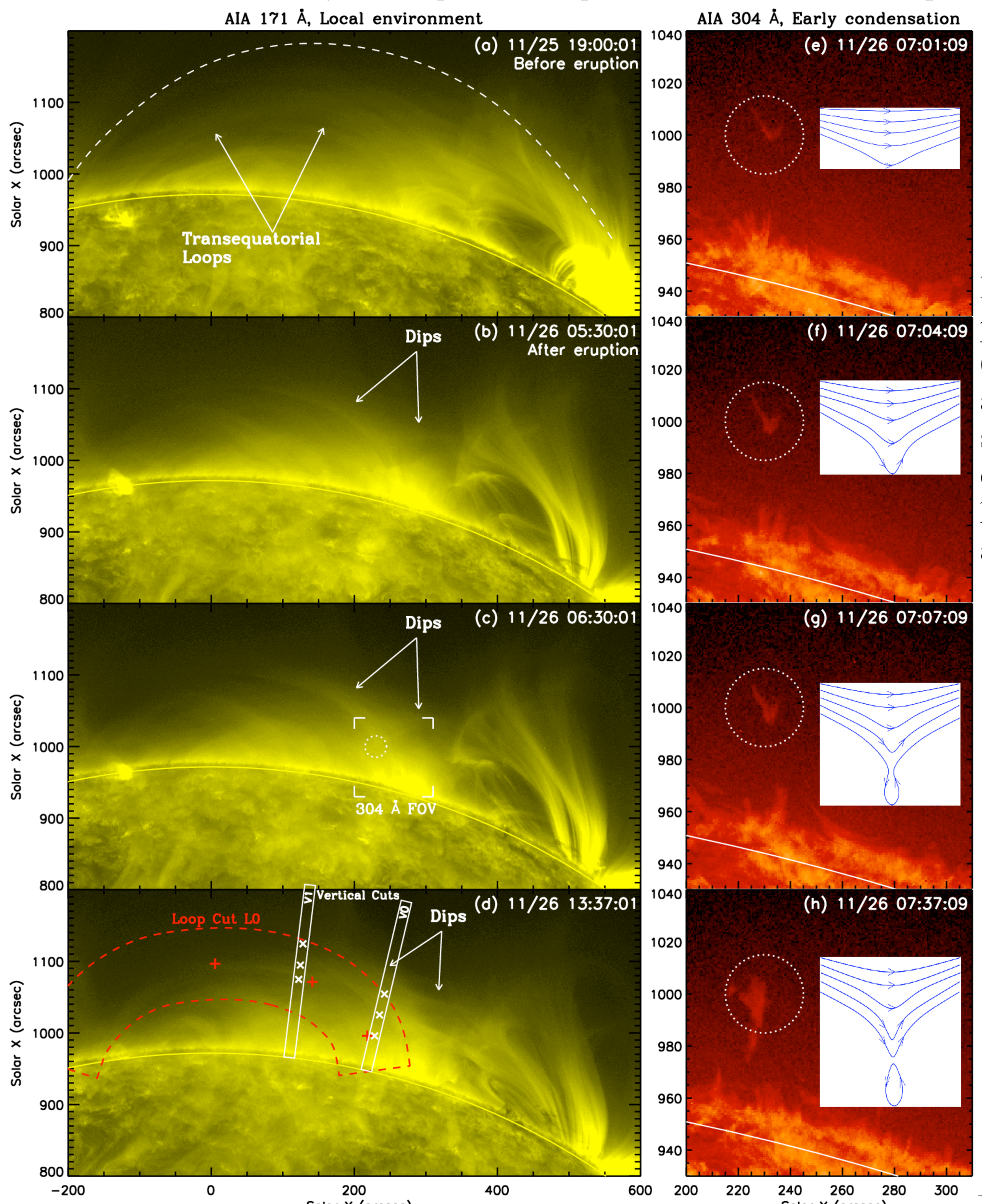


Fig. 2.3 (Right) — Space-time plots at AIA 193 (1.6 MK), 171 (0.8 MK), and 304 Å (0.08 MK), along vertical cut V0 in Fig. 2.4(d), showing hours of sequential cooling progressing toward lower heights, leading to condensation and formation of a prominence.

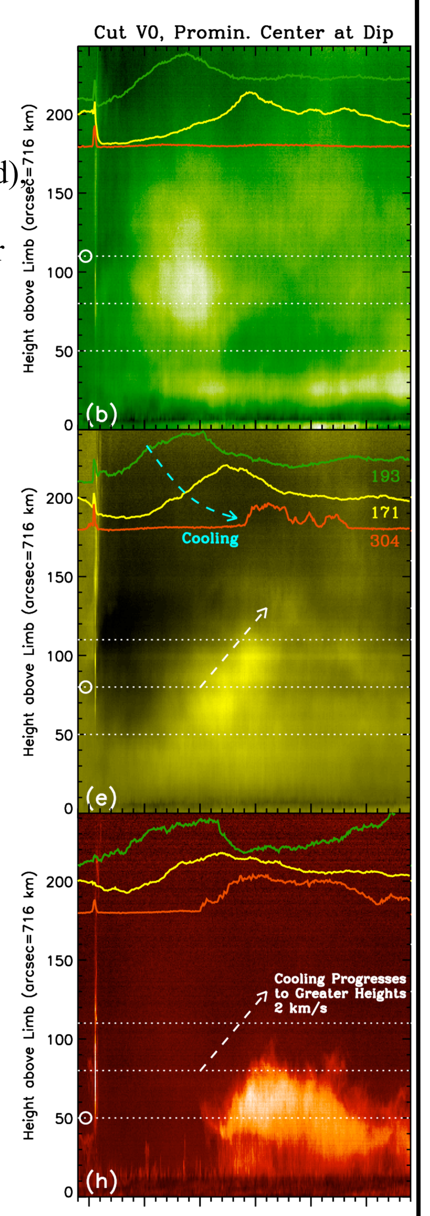


Fig. 2.4— **Left**: AIA 171 Å images showing dips (funnels) among trans-equatorial loops. Superimposed in (d) are cuts used to obtain space–time diagrams in Fig. 2.3. **Middle**: enlarged AIA 304 Å images showing the "V"-shaped initial condensation at the lowest dip, in a possible magnetic configuration shown in the insets, suggested by the theoretical model on the **Right** (Low, Berger, Casini, Liu, 2012).

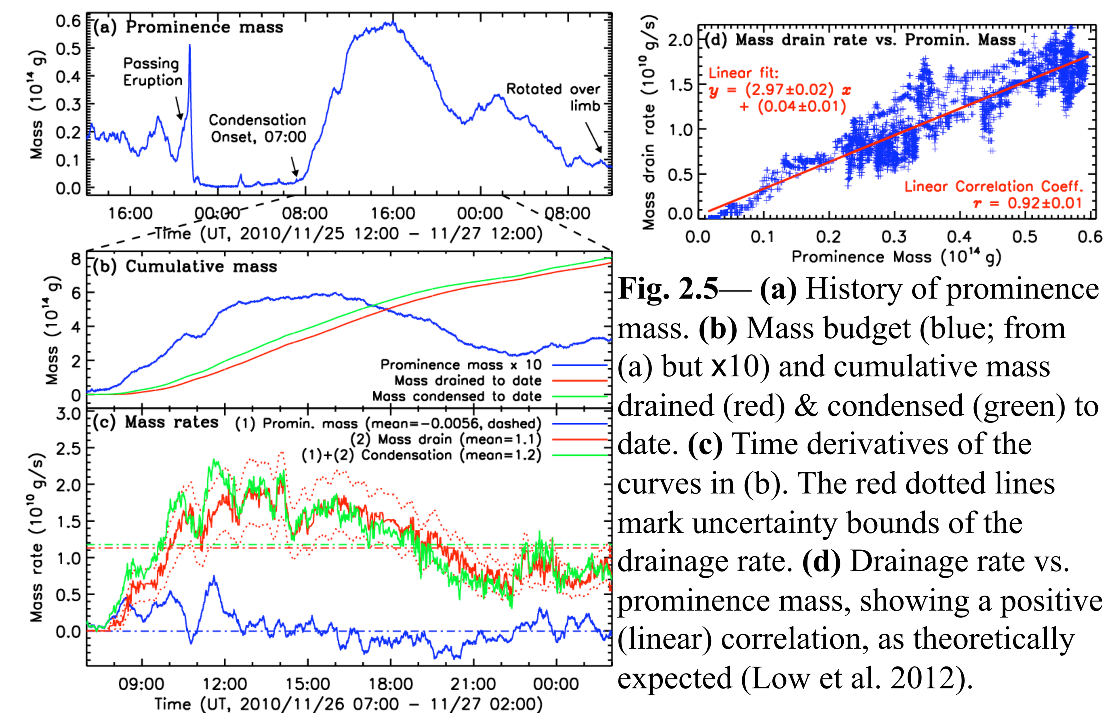


Fig. 2.5— **(a)** History of prominence mass. **(b)** Mass budget (blue; from (a) but x10) and cumulative mass drained (red) & condensed (green) to date. **(c)** Time derivatives of the curves in (b). The red dotted lines mark uncertainty bounds of the drainage rate. **(d)** Drainage rate vs. prominence mass, showing a positive (linear) correlation, as theoretically expected (Low et al. 2012).

4. Summary

1. Prominences: Return Flows of a magneto-thermal convection cycle (Berger et al. 2011; cf. Marsch 2008, McIntosh 2012), like rain on Earth.
2. *Macroscopically quiescent* but microscopically dynamic, delicate balance between mass supply (**condensation** by thermal/radiative instability) and slower than free-fall ($a = g_\odot/6$) drainage (**cross-field slippage** of cold, poorly ionized mass; Low et al. 2012)
3. Passage of Significant mass ~10^{15} g/day (1 billion ton; 10^{10} g/s), comparable to a fraction of the entire corona or a CME.
4. Inevitable *runaway cooling* (thermal instability) assisted by suppression of conduction across magnetic field lines, serving as perfect insulators.

2.2 Other Examples of Funnel Prominences

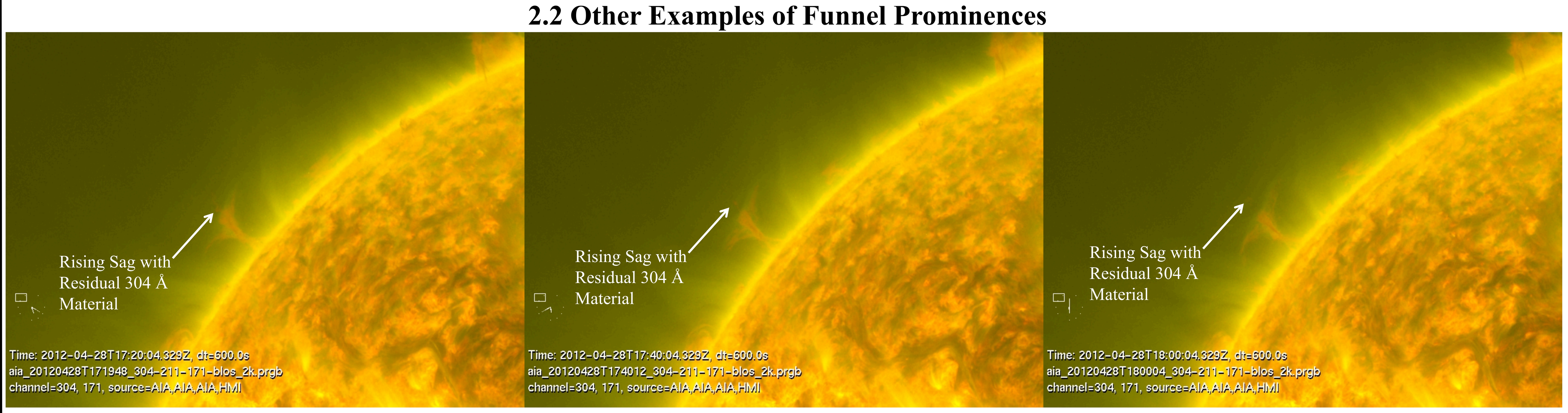


Fig. 2.6— Time sequence of a prominence (close-up of Fig. 1.2) seen at 304 Å (red) at the bottom of funnel-shaped coronal loops seen at 171 Å (yellow). It displays active drainage in its lower portion and simultaneous rise of shallow-dipped loops with very little 304 Å material in them in its upper portion (see a movie on the author's laptop). This is consistent with the scenario (Fig. 2.4, Berger et al. 2011; Low et al. 2012) that a breakdown of the froze-in condition leads to magnetic reconnection and cross-field slippage of cold, poorly ionized prominence material to lower field lines, while higher field lines lightened by mass unloading recoils upward due to an overcompensating Lorentz force.

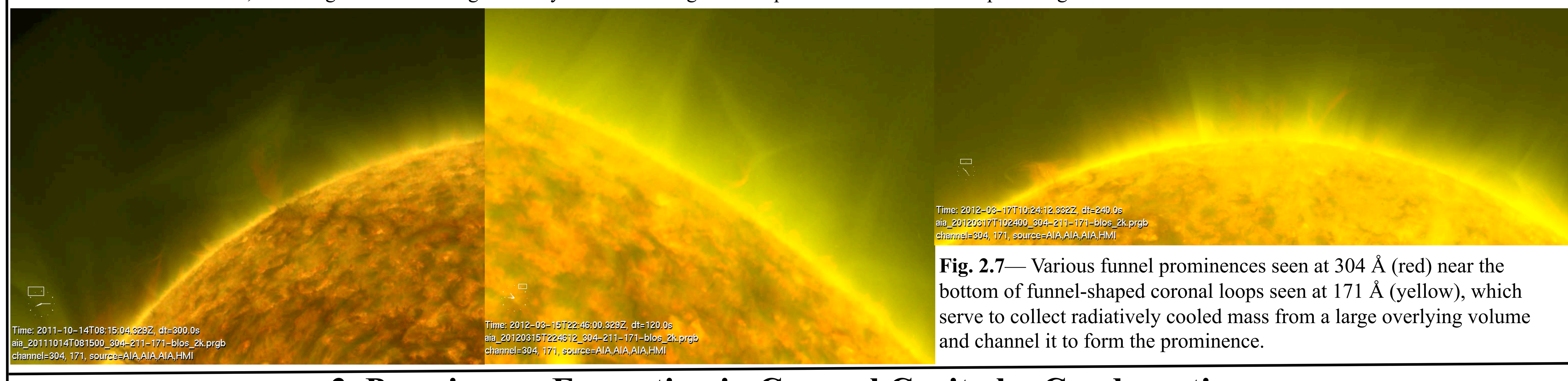


Fig. 2.7— Various funnel prominences seen at 304 Å (red) near the bottom of funnel-shaped coronal loops seen at 171 Å (yellow), which serve to collect radiatively cooled mass from a large overlying volume and channel it to form the prominence.

3. Prominence Formation in Coronal Cavity by Condensation

It is well known that large-scale polar-crown prominences often reside in the lower portion of (flux-rope) coronal cavities (e.g., Fig. 1.2), but not all cavities contain prominences. For the first time, prominence formation (via condensation) inside a coronal cavity has been captured, hours after an earlier prominence has been depleted by drainage. Hot plumes (Berger et al. 2008, 2010, 2011), likely from flux emergence, episodically intrude from below through the prominence into the cavity, supplying hot mass to be subsequently cooled and condensed.

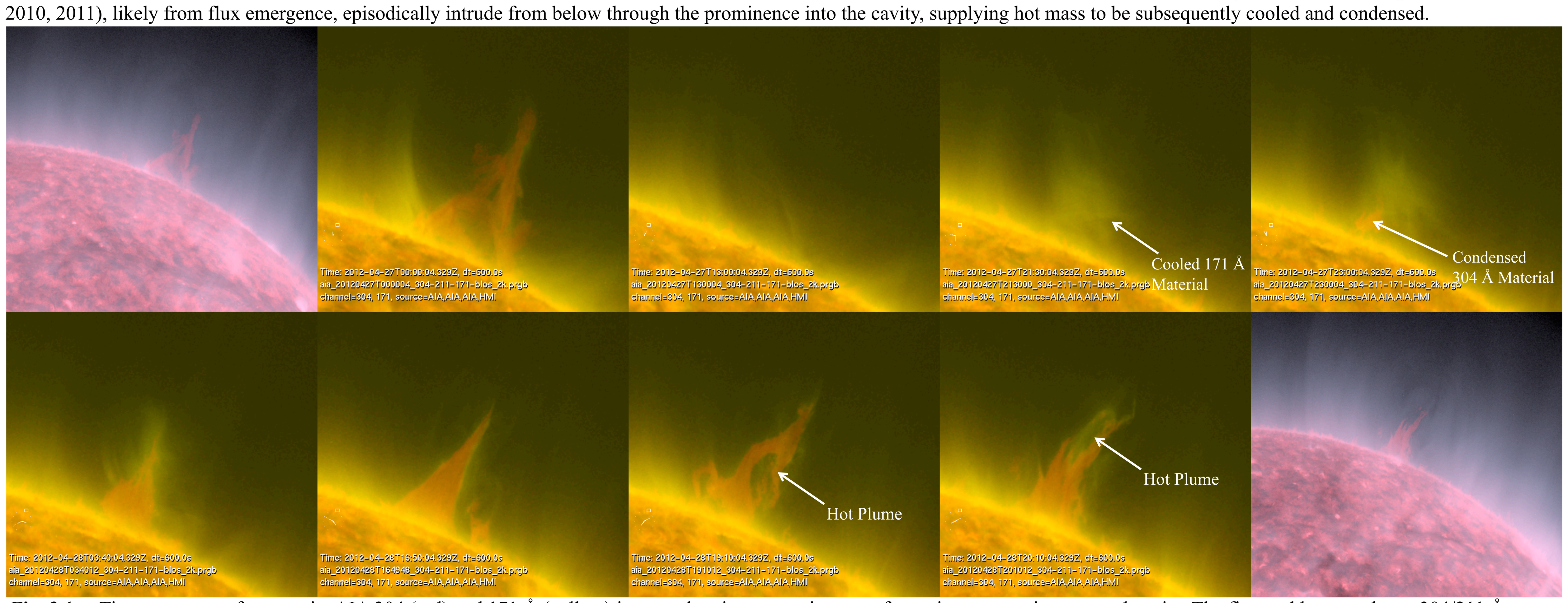


Fig. 3.1— Time sequence of composite AIA 304 (red) and 171 Å (yellow) images showing a prominence reformation process in a coronal cavity. The first and last panels are 304/211 Å versions of their neighboring panels in a larger field of view. After hours of absence of prominence, 171 Å (~0.8 MK) material appears in the lower portion of the cavity, followed by 304 Å (~0.08 MK) material condensing at the lowest height, gradually forming a new prominence, while the cavity becomes increasingly dark at 211. Note a hot (bright at 171) plume bubbling up.

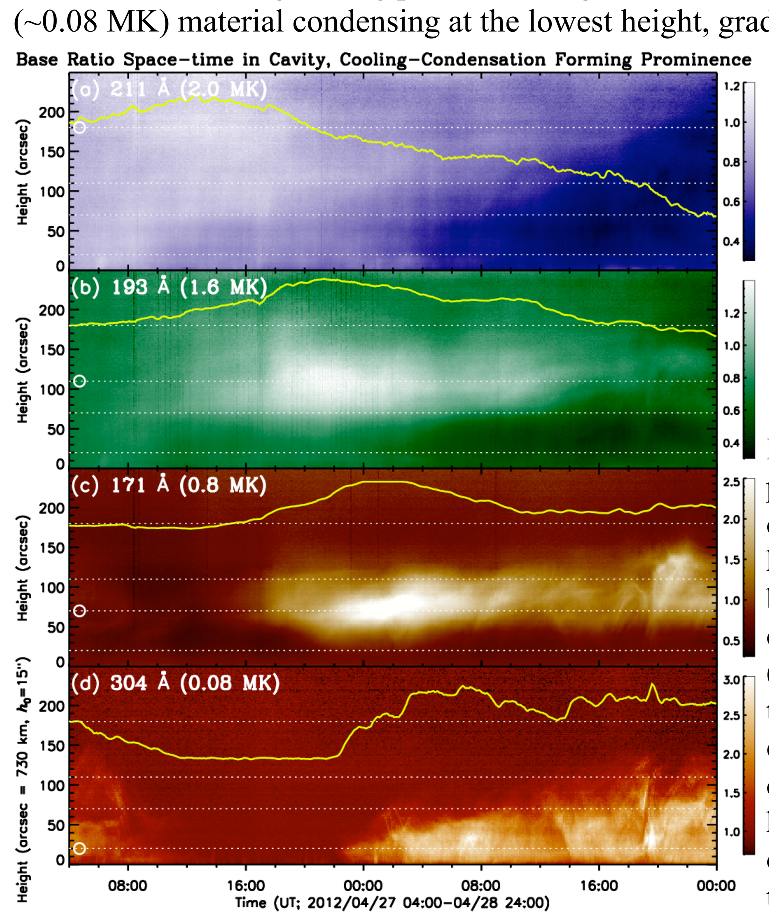


Fig. 3.2 — **Left:** AIA 211 Å base ratio space-time plots from a vertical cut across the coronal cavity (**Top**). The curve in each panel is a horizontal slice at the height of the brightest emission marked by an open circle. This height decreases from (a) to (d), with decreasing peak response temperatures of these AIA channels. The emission delayed in time indicates a cooling sequence progressing toward lower heights partly due to stratification with decreasing scale heights at lower temperatures.

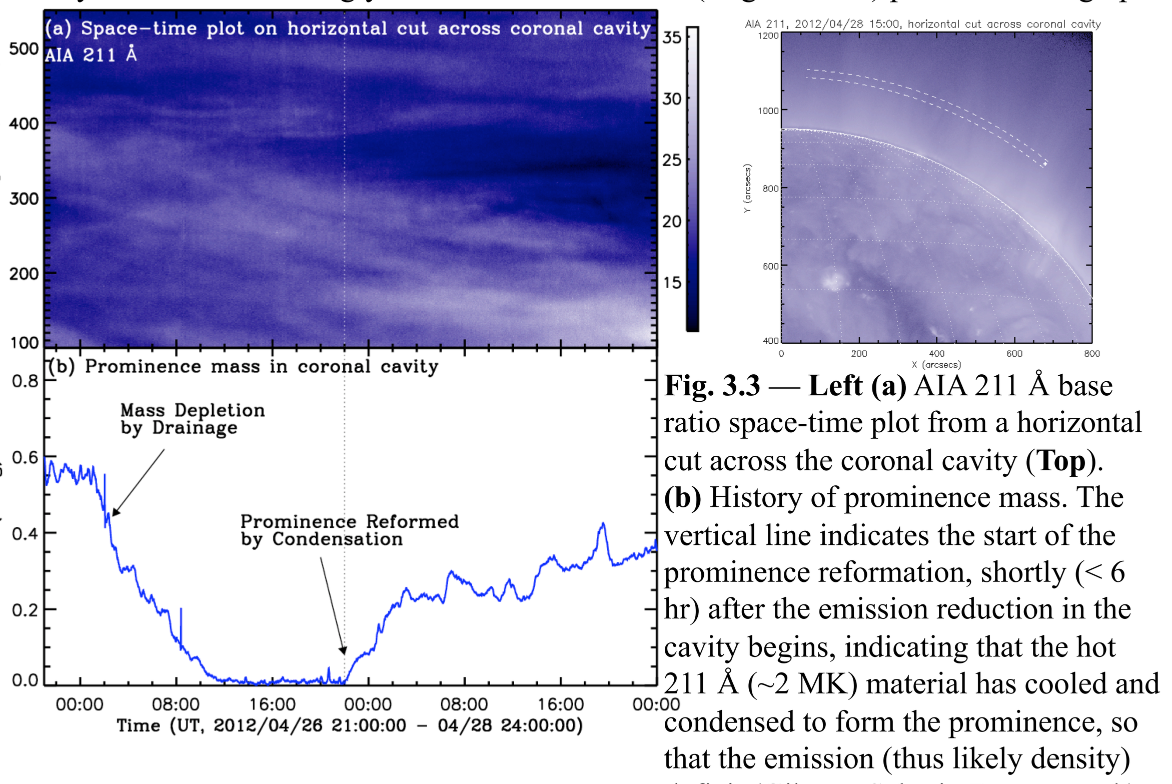


Fig. 3.3 — **Left (a)** AIA 211 Å base ratio space-time plot from a horizontal cut across the coronal cavity (**Top**). **(b)** History of prominence mass. The vertical line indicates the start of the prominence reformation, shortly (< 6 hr) after the emission reduction in the cavity begins, indicating that the hot 211 Å (~2 MK) material has cooled and condensed to form the prominence, so that the emission (thus likely density) deficit (Gibson, Schmit, Reeves et al.) in the cavity becomes more evident.