Using SDO/AIA to Understand the Thermal Evolution of Solar Prominence Formation

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Abstract

We investigated the thermal properties of prominence formation using time series analysis of Solar Dynamics Observatory’s Atmospheric Imaging Assembly (SDO/AIA) data. Here, we report the first time-lag measurements derived from SDO/AIA observations of a prominence and its cavity on the solar limb, made possible by AIA’s different wave bands and high time resolution. With our time-lag analysis, which tracks the thermal evolution using emission formed at different temperatures, we find that the prominence cavity exhibited a mixture of heating and cooling signatures. This is in contrast to prior time-lag studies of multiple active regions that chiefly identified cooling signatures and very few heating signatures, which is consistent with nanoflare heating. We also computed time lags for the same pairs of SDO/AIA channels using output from a one-dimensional hydrodynamic model of prominence material forming through thermal nonequilibrium (TNE). We demonstrate that the SDO/AIA time lags for flux tubes undergoing TNE are predicted to be highly complex, changing with time and location along the flux tube, and are consistent with the observed time-lag signatures in the cavity surrounding the prominence. Therefore, the time-lag analysis is a sensitive indicator of the heating and cooling processes in different coronal regions. The time lags calculated for the simulated prominence flux tube are consistent with the behavior deduced from the AIA data, thus supporting the TNE model of prominence formation. Future investigations of time lags predicted by other models for the prominence mass could be a valuable method for discriminating among competing physical mechanisms.

Unified Astronomy Thesaurus concepts: Quiescent solar prominence (1321); Quiet solar corona (192); Solar coronal heating (189); Solar extreme ultraviolet emission (1493); Solar filaments (1495); Solar physics (1476)

1. Introduction

Solar prominences are relatively cool ($\approx 10,000$ K), dense ($\approx 10^{11}$ cm$^{-3}$) structures suspended in the much hotter, more rarified corona. It is generally agreed that this material is supported by a long, low-lying, sheared or weakly twisted magnetic field, but how the cool, dense material comes to be in the corona is an area of long-standing debate (Gibson 2018). Important clues can be found in the hot plasma surrounding the prominence.

Many prominences in quiescent regions are surrounded by low-density areas known as prominence cavities (see reviews by Parenti (2014) and Gibson (2015)) and are often found to be hotter than the surrounding streamers (Karna et al. 2015; Bąk-Szteślicka et al. 2019). Cavities show significant structure, including areas of particularly hot plasma ($T > 2$ MK) that are observed around the embedded prominences when observed on the limb along their main axes. Hudson et al. (1999) and Reeves et al. (2012) report soft X-ray emission surrounding prominences, and Habbal et al. (2010) describe “hot shrouds” of plasma that are at least 2 MK surrounding prominences in visible and infrared eclipse data. Even when a prominence is not surrounded by a hot plasma core, the coronal-temperature plasma surrounding a prominence shows complex thermal structure (Kucera et al. 2012).

Models that seek to explain the presence of prominence plasma in the corona are generally based on three categories of underlying physical mechanisms: injection, levitation, and evaporation–condensation (see review by Karpen (2015)). The best-studied evaporation–condensation model invokes the thermal nonequilibrium (TNE) process, which has been explored extensively through theory and numerical simulations (Antiochos & Klimchuk 1991; Antiochos et al. 1999, 2000; Karpen et al. 2001, 2003, 2005, 2006; Karpen & Antiochos 2008; Xia et al. 2011, 2012, 2014a, 2014b; Luna et al. 2012; Xia & Keppens 2016) and is summarized in Section 4.1. Prominences are comprised of threads, which are skinny (<0.03), elongated concentrations of cold material (e.g., Lin et al. 2003). In TNE, heating near both footpoints of the long, sheared flux tubes supporting prominence threads drives chromospheric evaporation into the corona, followed by catastrophic condensation. If (as is likely) the footpoint heating is unequal, the flux tube is not deeply dipped, and/or the geometry of the flux tube is asymmetric, then the cool condensations can become dynamic and fall to the nearest chromosphere. Other conditions yield condensations that are quasi-static and grow in length for long intervals.

Prominences viewed along their axes often show “horns” reaching up into the cavity, particularly in the 171 Å EUV band ($T \approx 0.8$ MK) of the Solar Dynamics Observatory Atmospheric Imaging Assembly (SDO/AIA; Lemen et al. 2012; Boerner et al. 2012). This warm EUV emission from horn regions was found to be correlated with and connected to structural changes in adjacent cooler plasma observed in the 304 Å band, and is consistent with condensing prominence plasma as predicted by the TNE model (Schmit & Gibson 2013; Schmit et al. 2013). Other observational features that have been interpreted as evidence for TNE in prominences include counterstreaming (e.g., Zirker et al. 1998) and damping of longitudinal oscillations (Luna et al. 2014, 2018). Large regions of cool plasma appearing high in the corona without visible connections to the chromosphere have been observed...
called and raises the pressure of the transition region and chromosphere cools the coronal plasma increases rapidly. Then, thermal conduction of the energy to the density is low during the heating phase, and the temperature

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In the work presented in this paper, we take full advantage of the unique capabilities of the SDO/AIA data set, with its high temporal, spatial, and temperature resolution and coverage, in order to systematically investigate how cool, dense plasma collects in an off-limb prominence and to quantify how the plasma in the surrounding cavity evolves. We used the time-lag analysis method (Viall & Klimchuk 2012) to determine how widespread the thermal heating and cooling cycles are in the prominence and its surrounding cavity. We compared the time lags with those predicted by models of impulsive heating in active regions (ARs) and with those predicted by the TNE scenario, and discovered substantial differences between the AR and prominence time-lag maps. We conclude that the observed time lags in the prominence/cavity system are consistent with those predicted from TNE light curves and support the TNE model of prominence mass formation.

In Section 2, we describe the time-lag technique and summarize previous results on coronal heating using that method. In Section 3, we describe the AIA observations and the features revealed in the time-lag analysis of this observed prominence/cavity. In Section 4, we discuss TNE modeling and time-lag analysis of the model data. Section 5 discusses our results, comparing the model and data time-lag results and also comparing them to active region time-lag studies. Finally, in Section 6, we summarize our analysis, the conclusions we draw, and possible steps for the future.

2. Time-lag Analysis Technique

The time-lag technique is a systematic method for using light curves to measure plasma thermal evolution. In previous analyses, we used this technique to investigate the thermal evolution of coronal (Viall & Klimchuk 2012) and transition-region (Viall & Klimchuk 2015) plasma in active regions observed with SDO/AIA. SDO/AIA has six channels that are sensitive to plasma between $\approx 0.5$ and 10 MK. As plasma cools or heats through the temperatures that these channels measure, its emission intensity increases and decreases. When the density is roughly constant, the maximum brightness for a cooling plasma will occur first in the hottest channel, then in the next hottest, and so on, peaking in the coolest channel last. Plasma that is heated will exhibit the opposite emission pattern, peaking first in the coolest channel and last in the hottest channel. When plasma is impulsively heated, as in the coronal nanoflare scenario for heating AR flux tubes, the density is not constant (Cargill & Klimchuk 2004). In this case, the plasma density is low during the heating phase, and the temperature increases rapidly. Then, thermal conduction of the energy to the transition region and chromosphere cools the coronal plasma and raises the pressure of the transition region and top of the chromosphere, causing it to expand into the corona in a process called “chromospheric evaporation.” The coronal plasma is much denser during this cooling phase, and is much brighter than the heating phase. Even when lines of sight intersect many coronal flux tubes in different phases of heating and cooling cycles, the cooling phase is always much brighter than the impulsive heating phase and therefore dominates the emission at all times.

The time-lag technique identifies heating and cooling patterns by cross-correlating the light curves measured in the different SDO/AIA channels at a given pixel (location) as a function of their temporal offset. The cross-correlation value will reach its peak—denoted as the time lag—when the light curves are offset by the time for the plasma to evolve (either through heating or cooling) between those two temperatures. The convention set by Viall & Klimchuk (2012) is to set the hotter channel first. Therefore, a positive time lag—which indicates that the second channel maximum follows the first channel in time—results from cooling plasma, while negative time lags result from heating plasma.

We have applied the time-lag analysis extensively to models of impulsive coronal heating as well as to 16 observed active regions (Viall & Klimchuk 2012, 2013, 2015, 2017; Bradshaw & Viall 2016; Barnes et al. 2019). Five important results from these works are relevant for the prominence analysis here.

1. Positive time lags consistent with cooling are predominantly observed throughout all observed and modeled ARs, for time lags computed between all pairs of channels. Time lags consistent with heating are rarely observed. Positive time lags are predicted to dominate for coronal plasma that is impulsively heated to temperatures within or above the AIA bands, which then slowly cools after the heating ceases. Because the cooling plasma is always much brighter than the impulsively heated plasma, the cooling phase dominates the computed time lags.

2. Coronal plasma within a magnetic flux tube is predicted and observed to have the same time lag regardless of location along the flux tube. Because thermal conduction rapidly smooths out temperature gradients along the field, the coronal plasma within a flux tube will heat, increase in density, brighten, cool, and fade at nearly the same time. This is particularly compelling evidence of the robustness of the method, as the observations show common time lags along magnetic structures such as coronal loops, even though we test each pixel individually, without knowledge of the underlying magnetic structures.

3. Provided that the time window is not shorter than the plasma cooling time ($\approx 1$ hr for AR coronal conditions), the first two results are statistically independent of the duration of the time windows or the specific time window over which the time lags are computed (Viall & Klimchuk 2012).

4. When the plasma is stationary, without flows or temperature evolution, then the only source of emission variability is instrument noise, which produces random time lags with no spatial correlation and a very low cross-correlation value (Viall & Klimchuk 2016).

5. Time lags of zero indicate that the light curves in all of the channels increase and decrease in brightness at the same time. This occurs when flows bring plasma through a particular pixel, causing simultaneous brightening and dimming in all of the channels in which the plasma is emitting. Zero time lags also are predicted and observed in the transition region of impulsively heated flux tubes (Viall & Klimchuk 2015).
3. Observations

3.1. Prominence Observed in SDO/AIA

We analyzed six hours of SDO/AIA observations of an off-limb prominence and surrounding cavity observed on 2010 December 14 from 10:00 to 16:00 UT. Figure 1 shows images of the prominence taken at 13:20 UT in six AIA channels: 304 Å, 131 Å, 171 Å, 193 Å, 211 Å and 335 Å. One AIA pixel = 0.6". Though the AIA filters are sensitive to a broad range of temperatures, they are shown in order of the peak temperature that typically dominates the emission in these channels. The 304 Å channel images cool prominence material (≈0.05 MK) and the prominence-corona transition region. The other channels have peak sensitivities at 0.5 MK (131 Å), 0.8 MK (171 Å), 1.6 MK (193 Å), 2.0 MK (211 Å), and 2.5 MK (335 Å). We plot the AIA temperature response...
functions for the 335 Å (green), 211 Å (blue), 193 Å (orange), 171 Å (cyan), 131 Å (black), and 94 Å (red) channels in Figure 2.

The 94 Å channel, plotted in red, is shown for reference only. We did not use it for the time-lag analysis, as the count rates were extremely low. The extremely low count rates observed in the 94 Å channel are an important constraint. The 335 Å channel, though usable for the time-lag analysis, has lower count rates than active regions with peak temperatures near 3 MK typically have. These two observations indicate a lack of plasma above $\sim 3$ MK in this prominence/cavity system.

Transition-region emission can be very bright in all of the AIA channels, and can dominate the coronal emission wherever the line of sight (LOS) intersects both, yielding time lags of zero (Viall & Klimchuk 2015; Bradshaw & Viall 2016). For this study it was imperative to spatially isolate emissions from the cavity, the prominence-corona transition region, and classic chromosphere-to-corona transition region. Therefore, we selected a clearly visible, off-limb prominence for which the LOS is approximately parallel to its axis, aligned so that we could also observe the associated cavity.

Figure 1 shows the location of the cool prominence material, seen in 304 Å, relative to features in the other channels. Located above the cool prominence material is coronal emission, most obvious in the 193 Å, 211 Å, and 335 Å channels, which indicates that the coronal plasma is at temperatures of $T \approx 2$ MK. We circle this hot material in the 211 Å image and refer to it as the “core.” Surrounding the core is the prominence cavity, a quasi-circular region characterized by low emission in all channels, suggesting low densities, indicated with an arrow in the 211 Å image. Bright emission outside the cavity in 193, 211, and 335 Å shows that the surrounding corona is also at $T \approx 2$ MK.

Figure 3 shows a 200 x 200 pixel subfield in three representative channels (304 Å, 171 Å, 211 Å) at seven times that span the period of analysis. We computed time lags for this field of view, which encompasses the prominence and core and has high signal-to-noise ratios in all channels shown. In both Figures 1 and 3, the prominence appears dark due to continuum absorption. Overplotted in white on the images taken at 12:00, 13:00, 15:00, and 16:00 UT are outlines of features of interest. At 12:00 UT, we identify horns in 304 Å that emit at the same pixels as the horns in 171 Å emission, consistent with Schmit & Gibson (2013). Though horn structures are not visible in 211 Å, enhanced emission surrounds the location of the horns. For
images at 13:00 and 15:00 UT, white circles outline three bright blobs of plasma in 304 Å. As with the horns, the two blobs seen at 13:00–14:00 UT are at the same locations in both channels, within a larger area of enhanced 211 Å emission. The area within the diamond-shaped outline, whose apex is above bright features in 304 Å emission, is part of the cavity outside the prominence (see Section 3 for further discussion). In the final image, taken at 16:00 UT, the hot core region of enhanced 211 Å emission above the dark prominence is circled. As with the blobs, the bright cores are at the same pixel locations as the emission in 304 Å, 171 Å, and 211 Å at this time. For example, the third blob is encapsulated by the core. These observations demonstrate that the hot, multithermal coronal plasma lies above the prominence, yet is connected with the cooler prominence plasma, consistent with previous work.

3.2. Observed Time-lag Features

We used the time-lag technique to determine the temporal relationship between thermal plasmas at different temperatures in the observed prominence/cavity system. To compute the time lags, we first made light curves for each pixel in the 131 Å, 171 Å, 193 Å, 211 Å, and 335 Å channels, using six hours of data sampled at a cadence of 12 s. Together, these channels record plasma evolution between 0.5 MK and 2.5 MK. We did not use the 304 Å observations for the time-lag computation because the He II line that dominates the 304 Å emission in prominences is optically thick and requires non-local thermodynamic equilibrium (non-LTE) modeling in order to be properly interpreted (e.g., Labrosse & Gouttebroze 2001).

We calculated the time lag at each pixel over the six-hour time window for each of the ten channel pairs. Maps of the time lags are displayed in the top rows of Figures 4. The center of the first channel peaked in brightness first, and blue and green indicate negative time lags (where the second channel peaked in brightness first). Olive green represents a time lag of zero, signifying highly correlated variability between the two channels.

The bottom three rows of Figure 4 show the time lags computed over two-hour subintervals within the larger six-hour window: 10:00–12:00, 12:00–14:00, and 14:00–16:00 UT. In this case, we only tested for time lags between ±3600 s (1 h), and the color bar is adjusted to highlight the shorter time lags. For the two-hour subintervals, we do not test for time lags longer than ±1 hr, as computations of longer time lags use less than half of the time series and no longer capture the general behavior of the plasma (Viall & Klimchuk 2012). In white, we overplotted the outlines of the features highlighted in Figure 3 that were visible during the given two-hour interval.

We find that zero time lags are predominantly associated with the prominence, as well as the limb of the Sun. This is consistent with both transition-region dynamics (i.e., the prominence-to-corona and chromosphere-to-corona transition regions) as well as large flows. In general, we find more positive than negative time lags surrounding the prominence, but the negative time lags comprise a significant fraction of the observations. There are some spatially coherent patches that exhibit similar time lags. However, unlike ARs, full magnetic loop-like structures with the same time lag are not present. Last, the time-lag results depend on the time interval of analysis, and locations of positive time lags can be locations of negative time lags when computed over the next time interval—and vice versa.

The features that we identified in the images as correlated at different temperatures are focal points for our detailed interpretation of the observed time-lag maps, which include a complex mix of positive, negative, and zero time lags. One location consistent with a cooling plasma is designated by the diamond above and to the left of the leftmost horn, as indicated in Figures 3 and 4 in the 10:00–12:00 UT rows. The center of this diamond is near the pixel at coordinate (x = 40, y = 110). This ≈50 × 25 pixel area exhibited mostly positive time lags in all channel pairs, except for 171–131 Å, for this six-hour interval. This indicates that the dominant variability in the light curves for these six hours was due to cooling from 2.5 MK to 0.8 MK. The random mix of positive, negative, and zero time lags between the 171 and 131 Å channels in the diamond indicates that not much plasma cooled into the 131 Å channel at 0.5 MK.

However, few locations in the time-lag maps exhibited such clear, full cooling from the hottest to cooler temperatures. For example, the three blobs (small circles in the windows at 12:00–14:00, 14:00–16:00, and 10:00–16:00 UT) exhibit mostly positive time lags in the 171–131 Å channel pair, indicating cooling from 0.8 to 0.5 MK. The remaining channel pairs, except for 335–193 Å and 335–211 Å, are dominated by negative time lags, indicating that the heating phase was also observed.

The 211 Å, 193 Å, 171 Å, and 131 Å channels each have a single maximum sensitivity in the temperature range of the cavity and core, making them easier to interpret. On the other hand, the 335 Å channel is complex, with three peaks in sensitivity: one near 2.5 MK, one near 0.8 MK (near the 171 Å sensitivity peak), and one near 140,000 K that would be bright in the prominence-to-corona TR emission. Since plasma at all three temperatures is expected to be present in the prominence/cavity system, time lags in pairs with the 335 Å channel are best interpreted in the context of the pairs between channels with less complexity. Given the time lags observed between the simpler channel pairs, the positive lags observed only in pairs 335–193 Å and 335–211 Å likely indicate that the plasma in these three blobs emitted at temperatures in the cool portion of the 335 Å sensitivity.

The final time lags we highlight are those of the three horn structures, marked by white arcs in the 10:00–12:00 UT windows of Figures 3 and 4. The area between the right two horns exhibited positive time lags between the 211 Å, 193 Å, and 171 Å channel pairs, consistent with cooling from near 2 MK to 0.8 MK in this two-hour window. The behavior is a random mix of positive and negative time lags in the pairs with 335 Å and the 171–131 Å pair, indicating that the plasma did not get much hotter than 2 MK nor much cooler than 0.8 MK. The areas near the other horns also behaved erratically: spatial
Figure 4. Time-lag maps computed for the 200 × 200 pixel area shown in Figure 3. Each column shows maps for the same pair of channels, labeled on the top, while rows show maps calculated over different time windows, labeled on the left. Right color bars indicate the time-lag values, which span ±7200 s for the top row and ±3600 s for the bottom three rows. Top and bottom panels show different channel pairs for the same time intervals. White outlines indicate areas of interest from Figure 3.
swaths of negative, positive, and zero time lags, with no one type predominating, signify that both heating and cooling signatures were observed.

4. Modeling Results

4.1. The Thermal Nonequilibrium Model

The TNE paradigm explains the presence of cool, dense material suspended in the hot, rarified corona as a straightforward consequence of two properties: coronal heating concentrated near the chromosphere on scales approximately 10% of the length of the flux tube supporting the prominence thread, and magnetic shear localized near polarity inversion lines (Mok et al. 1990; Antiochos & Klimchuk 1991). Under these conditions, the total radiative losses exceed all energy inputs and no plasma equilibrium exists, motivating the term "thermal nonequilibrium." The resulting pressure drop causes a catastrophic collapse, pulling coronal plasma into a small region in which the temperature falls and the density rises to chromospheric levels. The subsequent evolution of the condensation depends critically on the specific magnetic geometry and relative heating at the two footpoints: in some cases, the condensation will settle in a dip and grow, while other conditions cause small, dynamic condensations to form and fall onto the closest chromospheric footpoint. In this scenario, a prominence is composed of many threads that occupy only a portion of long, low-lying flux tubes rooted in narrow filament channels. The cool, dense threads preferentially collect in dipped sections of the field or counterstream and disappear.

We used our well-established one-dimensional hydrodynamic code, ARGOS, to model the formation and evolution of a TNE-based prominence thread, in a manner similar to previously published calculations (Antiochos et al. 1999, 2000; Karpen et al. 2001, 2003, 2005, 2006; Karpen & Antiochos 2008; Xia et al. 2011, 2012, 2014a, 2014b; Luna et al. 2012). Based on the simulation results, we forward modeled the simulated light curves in SDO/AIA, and computed time lags from these light curves following the same procedure as described in Section 2 for the observational analysis.

The geometry is a slightly dipped flux tube, with a uniform cross-sectional area and a length of 320 Mm; this includes two 40 Mm chromospheric-photospheric sections. The atmosphere is treated as a fully ionized plasma with a minimum temperature of $3 \times 10^4$ K, as in our prior studies. The solar radiative losses are limited by radiative transfer below $3 \times 10^4$ K; these effects are not included in our model. The chromosphere is maintained at around $3 \times 10^4$ K by tailoring the optically thin radiative loss function; for details on this procedure, see Karpen et al. (2005).

The initial loop was populated by imposing a small uniform background heating, which set up a stationary equilibrium with a maximum coronal temperature of 2 MK, consistent with the standard scaling laws (Rosner et al. 1978). After the system relaxed, spatially localized heating with a scale height of 10 Mm was imposed at each footpoint; the maximum localized heating rate at the left footpoint was 75% of that at the right footpoint. Further details of the simulation methodology and parameters are given in Karpen et al. (2001, 2005).

Figure 5 shows the temperature, velocity, and density as functions of loop length at four representative times during the simulation. Here, we define $t = 0$ s to mark the start of the localized footpoint heating. In response to the localized heat input, the loop temperature increases everywhere for approximately 2.5 hr, at which point the peak temperature is $\approx 2.9$ MK (Figure 5, second row). Because the right side of the loop is heated more strongly, the maximum temperature is on that side. Evaporative upflows ($v \lesssim 20 \text{ km s}^{-1}$) are maintained in the loop legs and the coronal density increases.

At around 2.1 hr, a dense, cool condensation begins to form near the middle of the flux tube, slightly closer to the left side (Figure 5, third row). At this point, the entire loop has cooled by about 1 MK; the maximum temperature on the left side is 1.5 MK while the right side peaks at 2.0 MK. The condensation continues to grow (Figure 5, bottom row), while evaporative upflows in the loop legs continue to supply mass to the loop. The coronal segments of the loop slowly increase in temperature, with the left side heating back up to 2.0 MK and the right side reaching 2.3 MK.

In this scenario, a condensation is one thread of a multithreaded prominence embedded in a sheared-arcade magnetic structure. The coronal plasmas contiguous with the threads (i.e., occupying the rest of the flux tubes; see bottom row of Figure 5) collectively comprise the cavity, along with hot plasma in flux tubes not undergoing TNE or containing small, transient condensations that disappear quickly. Therefore, the prominence and cavity are intrinsically linked, with much greater volume occupied by coronal material than by cool plasma. TNE also can occur in other filament-channel structures, such as flux ropes (e.g., Fan & Liu 2019), with condensation distributions that could differ substantially from those of a sheared arcade (see Section 5).

We forward modeled the AIA emission for this simulated flux tube as a function of time, by convolving the computed temperature and density with the AIA temperature response functions (Figure 2). For consistency with the simulation constraints, we set all emission from plasma at temperatures $= 30,000$ K equal to zero (Karpen et al. 2001), as we are not assessing the optically thick emission that dominates at these temperatures. Figure 6 shows the simulated AIA emissions in the 131 Å, 171 Å, 193 Å, 211 Å, and 335 Å passbands as a function of position along the loop and time, downsampled from the simulation spatial resolution to the corresponding AIA pixel size.

After footpoint heating is turned on, the increased density throughout the loop causes the intensity to increase in all channels until the condensation forms. Thereafter, the flux tube is divided into two coronal-temperature segments separated by the cool, growing condensation, with a transition region at each end. For convenience, in the following discussions, we refer to the left side of the flux tube as the weakly heated side and the right side of the flux tube as the strongly heated side, even though the heating rates are not greatly different.

4.2. Time-lag Features in TNE model

Next, we computed the time lags between the 10 pairs of light curves at each simulated AIA pixel over four windows: one window from 0 to 12 hr, and three successive two-hour subwindows from 0 to 2, 2 to 4, and 4 to 6 hr. All of the windows begin after the asymmetric footpoint heating has been turned on. The first two-hour window covers the phase of slow heating, followed by rapid cooling as the condensation begins to form. The second two-hour window covers the collapse of the condensation, the post-condensation temperature rise in the
coronal portions of the loop, and the damped oscillation of the growing condensation. In the final two-hour window, the cool condensation continues to accrete mass and grow in length, while the coronal segments of the loop do not evolve much.

In Figure 7, the time lags for the four intervals are shown in the same order of channel pairs as the observations, beginning with the 171–131 Å channel pair results on the left. Following the observed time-lag calculation, we computed the time lags from \( \pm 7200 \) s for the 12 hr window, and \( \pm 3600 \) s for the two-hour windows; the corresponding values are indicated by the color bars to the right of the plot. The time-lag “maps” are one-dimensional, with time lags as a function of position along the one-dimensional model loop. For visual interpretation purposes, therefore, we artificially gave the time-lag maps a finite width. As with the observed prominence/cavity system, negative, positive, and zero offset time lags are all found for the simulated TNE model, and more positive than negative time lags are present.

The intensity profiles and the time-lag maps show that the flux tube exhibits three main types of responses according to location: the strongly heated right side (pixels \( \approx 300–400 \)); the weakly heated left side (pixels \( \approx 100–200 \)); and the initial condensation site (pixels \( \approx 200–250 \)). The strongly heated side exhibits different time-lag patterns than the weakly heated side. The section containing the condensation manifests complex time-lag behavior that is generally different from either of the loop legs; in particular, only this section exhibits the time-lag signature of cooling to prominence temperatures. The time lags

Figure 5. Temperature, velocity, and density as functions of position along the simulated loop at four representative times. Top row shows the initial static equilibrium. Second row shows the loop properties after the asymmetric footpoint heating has been turned on, but before the condensation has formed. Third row shows a snapshot of the condensation forming. Bottom row shows the end of the simulation, after the condensation has been slowly growing.
depend strongly on the window chosen, with the twelve-hour window results differing significantly from the two-hour windows; each two-hour window is different from the others, which reflects the different evolutionary phases captured by each window.

The modeled flux tube starts with a peak coronal temperature around 2 MK, emitting most strongly in the 211 Å band. The first two-hour time window covers the initial coronal temperature increase following the imposition of localized heating at both footpoints, when the whole loop heats up to temperatures near 2.5 MK, around the 335 Å sensitivity peak. The negative time lags computed over this first two-hour window between channel pairs 193–171 Å and 211–171 Å are the result of this heating. Later in this time window, the flux tube cools asymmetrically as the ambient coronal density rises through chromospheric evaporation and the radiative losses increase. The strongly heated side cools less than the other side and remains near 1.8 MK, in the peak sensitivity of the 193 Å and 211 Å bands. During the cooling phase, the plasma is denser and brighter than it is right after the asymmetric footpoint heating has turned on, so positive time lags dominate the pairs with 335 Å, as well as the 211–193 Å pair for the hotter, right side of the loop. Much of the hotter side shows zero time lags, which can occur whenever plasma cools into, but not through, the temperature response of the cooler bands (193, 171, and 131 Å), regardless of the heating mechanism (Bradshaw & Viall 2016; Viall & Klimchuk 2017). On the other hand, part of the weakly heated side cools to temperatures near 0.7 MK, which yields positive 211–193 Å time lags. The other channel pairs are dominated by the density changes, rather than temperature. As a result, a mix of positive and negative time lags appears along the loop for this time window, reflecting the temperature range along the loop at any given time.

The second time window (2–4 hr) contains the catastrophic collapse of the cool condensation, the formation of a pair of shocks that propagate to the loop footpoints, and the damped oscillation of the condensation until it finds its equilibrium position. The “loss” of the excess coronal density to the condensation causes the coronal segments of the loop to heat up again in response to the ongoing footpoint heating, except at the condensation site. The shocks also contribute to the coronal temperature rise (Karpen et al. 2001). The temperature remains below 2.5 MK in nearly all of the flux tube, so after the condensation forms, the 335 Å and 171 Å channels are sensitive to the same ~1 MK plasma. The weakly heated side (pixels 100–220) exhibits a mix of positive and negative time lags, due to its nonuniform temperature structure. Negative time lags around pixel 100 for the 193–171 Å pair are due to the plasma reheating, while many of the zero time lags can be attributed to the motion of the condensation as it oscillates around its final position. Positive time lags near the condensation around pixel 190 are the result of the cooling that dominates as the condensation begins to grow. The condensation itself manifests a complex mixture of negative and positive time lags, with the effects of cooling, density changes, and damped oscillations all playing a role. On the strongly heated...
side of the flux tube (between pixels 300 and 400), negative time lags reflect the reheating of plasma from 0.8 to 2 MK (i.e., from the 171 Å band through 193 Å up to 211 Å).

In the third time window (4–6 hr), the condensation grows steadily with little temperature or density variation in the remainder of the flux tube. The light curves along the coronal segments vary slightly. In observations, we suspect that the noise variations would be larger than emission fluctuations from these tiny physical changes. On the other hand, cooling plasma adjacent to the condensation produces large changes in the light curves, consistent with the ongoing accretion of prominence material from the hot, overdense corona. The positive time lags are produced by cooling plasma in the 211–193 Å and 211–171 Å channel pairs. Here, the 335 Å band is sensitive to cool plasma, so the negative time lags between 335 Å and the other channels near the condensation are also signatures of the cooling plasma.

The time lag computed for the entire 12 hr is a mixture of all of these effects, with the physical process producing the largest intensity change determining the time lag. The coronal section on the strongly heated side (pixels 300–400) yields a mix of negative and positive time lags as a function of position along the loop and the channel pair. The weakly heated section (pixels 100–200) has positive time lags in almost all of the

Figure 7. Time lags computed at each AIA pixel of the simulated loop, between the ten possible AIA channel pairs. Top row shows the time lags computed for a 12 hr time window (0–12 hr). Bottom three rows show the time lags computed over three two-hour subwindows (0–2, 2–4, and 4–6 hr, respectively). Time lags are measured from ±7200 s for the 12 hr window, and ±3600 s for the two-hour windows. Red, orange, and yellow indicate positive time lags. Green and blue indicate negative time lags. Olive green signifies strong correlation at no temporal offset. Black generally occurs where the plasma is at 30,000 K and we set the emission to zero. Pixel zero corresponds to the left, more gently heated side of the loop.
channel pairs for the 12 hr window—except for the 171–131 Å pair, which is dominated by time lags of zero.

5. Discussion

The time-lag measurements must be interpreted with some caution. As was the case for the prior time-lag studies on AR observations, any given pixel is likely to contain many flux tubes along the line of sight contributing to the observed emission. If filament channels, each flux tube may or may not be undergoing TNE, and those that are may be at different phases in their TNE cycles (e.g., Luna et al. 2012). In contrast, the simulation analyzed here only represents a single flux tube undergoing one type of TNE event; highly dynamic TNE cycles of small condensation formation and disappearance via falling to the chromosphere are also possible. For the simulation, we deliberately chose the time windows for their relationship to the formation and growth of the condensation and to avoid capturing partial phases. This type of precise time window choice is unlikely to be feasible in analyzing observations, particularly given the ensemble of flux tubes present. Furthermore, shorter time windows are more likely to capture only part of the heating or cooling phases, producing time lags that do not represent the overall temperature evolution.

We also note that noise was not included in the simulated light curves. During the final phase of this simulation (third window, bottom panel of Figure 7), the temperature and density barely vary in the coronal portions of the loop, yet the resulting small variations in the light curves yield statistically significant time lags. In the observations, the instrument noise would likely dominate over such small fluctuations in the light curves. Under these circumstances, the observed light curves will be uncorrelated and the “time lags” for each pixel will be random (Viall & Klimchuk 2016).

Finally, as described in Section 3, the AIA channels are sensitive to a range of temperatures, and in some cases, have multiple peak sensitivities (Figure 2). Plasma temperatures in this cavity are near 1–2 MK, with negligible emission at temperatures above 2 MK. This makes the 211 Å, 193 Å, 171 Å, and 131 Å channels easiest to interpret, while time lags in pairs with the complex 335 Å channel are best interpreted in the context of the other pairs.

Despite these considerations, the time-lag measurements presented here provide new insights into the prominence/cavity system and TNE formation. We find three important aspects shared by the time lags measured in the observed and simulated prominence/cavity systems, which differ from the time lags that were previously measured in observed and modeled active regions.

1. We measured many negative time lags in both the observed and modeled prominence/cavity systems. In contrast, observed active regions and ARs modeled with impulsive filament heating predominantly exhibit positive time lags, with very few negative time lags.

2. The time lags in the modeled and observed prominence/cavity depend strongly on location: in the model, the condensation and the adjacent coronal segments comprise three distinct sections once the condensation has formed, and the observations also contain significant variations between the prominence and its surroundings. Furthermore, the addition of two new transition regions bounding the condensation introduces additional time-lag structure in the model flux tube. This affects the minimum and maximum temperatures of each loop section as a function of time, and therefore dictates in which passbands each section emits strongly. The condensation and its surrounding condensation-to-corona transition region produce time-lag signatures different from those of either coronal leg. In contrast, modeled and observed AR flux tubes are highly coherent, exhibiting the same time-lag signature along the entire coronal portion of the flux tube.

3. The observed and modeled prominence/cavity time lags vary from one time window to the next, even switching from negative to positive and vice versa. In contrast, the observed and modeled AR time lags are roughly constant for all time windows.

In summary, the defining feature of the time lags associated with TNE is their complexity.

The time-lag method can be applied to any model of prominence mass formation that makes quantitative predictions concerning the optically thin, collisional EUV emission. We have compared the cavity emissions observed around a prominence and found them to be qualitatively similar to predictions derived from modeling TNE in a single dipped flux tube. The TNE model is highly developed and able to predict the EUV emission expected in coronal structures undergoing this process, including more complex simulations of the cavity system (e.g., Luna et al. 2012; Xia & Keppens 2016; Fan & Liu 2019).

These simulations also show emissions that apparently represent the horns observed in, e.g., the 171 Å band as an extension of cooler material observed in 304 Å. TNE simulations have demonstrated that horns are generally associated with the presence and growth of condensations. In contrast, levitation and injection models of prominence material do not predict the time-dependent plasma properties in the cavity above the prominence, which must be explained by some other means.

Our observational analysis also detected a hot cavity and core surrounding the prominence, consistent with earlier studies (e.g., Hudson et al. 1999; Reeves et al. 2012). We interpret this core as a TNE signature of the dense, hot material piling up outside the condensation (Karpen et al. 2003). Fan & Liu (2019) have modeled a prominence/cavity as an emerging 3D flux rope including evaporation, yielding condensations, and found a hot central core associated with long, shallowly dipped field lines near the flux rope axis. Dissipation at magnetic flux surfaces, through reconnection or hyperdiffusion, has been proposed as an alternative explanation for the hot core (van Ballegooijen & Cranmer 2008; Reeves et al. 2012).

Other models of prominence mass formation, including injection, levitation, and other evaporation-condensation models like magnetothermal convection (see Karpen 2015), have not been developed to the extent necessary for quantitative predictions of related EUV coronal emissions. Without the requisite effort, these models also would be good candidates for making time-lag predictions.

We conjecture that the time-lag signatures in other models may be different from TNE signatures. For example, injection or levitation models that create prominence threads by injecting or lifting chromospheric plasma directly into the corona are likely to exhibit strong correlations with zero time lag at all of
the spatial locations (pixels) the material crosses. If the material remains at chromospheric temperatures, as in simple versions of levitation or cool-mass injection models, then no coronal EUV emission comes from the prominence plasma. All of the coronal EUV light curves would decrease at the same time as the cool plasma crosses the pixel, and would exhibit zero time lag. In another model for prominence mass formation, condensations occur when field lines reconnect to form longer ones, reducing thermal conduction along the loops (Kaneko & Yokoyama 2017). Because this model does not produce heating signatures in the corona, we expect that its time lags would be exclusively dominated by plasma cooling signatures.

In general, it is unlikely that other models of prominence formation will exhibit the same time-lag signatures of heating and cooling cycles that characterize TNE. However, whether each model produces unique time-lag patterns would require detailed thermodynamic modeling and has yet to be determined.

6. Conclusions

We report the first time-lag measurements derived from observations of a prominence/cavity system on the limb, and compare them with the first time-lag calculations of a simulated prominence thread formed by TNE in a long, low-lying, dipped flux tube. The time-lag technique has revealed important clues about coronal heating in observed and modeled active regions, so we also compare our prominence/cavity analysis with the well-established signatures of coronal nanoflare-heated flux tubes. By analyzing six hours of SDO/AIA images in several passbands, we find that the observed prominence is surrounded by a low-density cavity and hot ($\approx 2$ MK) core plasma, consistent with previous cavity studies (Parenti 2014; Gibson 2015). Little emission was detected at temperatures hotter than $\approx 2.5$ MK, which placed an upper temperature limit on our TNE model. We also find that slightly cooler ($< 1-2$ MK) plasmas observed in AIA’s coronal channels outline and surmount the prominence material in 304 Å, as found by Schmit & Gibson (2013). These horns and blobs probably include the prominence-to-corona transition region, as well as the dense coronal plasma about to condense. In view of the two-dimensional nature of the images, we conclude that the prominence plasma is embedded within the hot core and adjoined by horns and blobs, in agreement with the predictions of the TNE model.

The time lags calculated from light curves of the observed and simulated prominence/cavity systems measure how the plasma evolves in time. We find evidence of plasma cooling from coronal temperatures to those below the AIA passbands, consistent with cooling to prominence temperatures. In contrast to nanoflare heating and cooling cycles, where the whole flux tube evolves in unison and the cooling phase always dominates the light curves and time lags, the simulated TNE loops exhibit highly complex time-lag behaviors as a function of time and location along the loop. Complexity is a defining feature of TNE time lags, because only part of the flux-tube plasma—essentially, the excess evaporated into the corona by the localized heating—fully cools and forms a prominence thread. The adjoining coronal segments do not cool to chromospheric temperatures, and both cooling and heating phases have high-density plasmas that contribute significant emission to the light curves.

We find that the observed time lags for this prominence/cavity are consistent with prominence threads being formed through TNE in a magnetic structure consistent with the sheared-arcade model for filament channels (DeVore & Antiochos 2000). However, this does not preclude other models for the magnetic structure or mass formation from demonstrating their viability as explanations of the reported prominence/cavity properties. Despite the complexity, in certain cases we found local patterns consistent with plasma that cools from coronal to prominence temperatures. These locations (e.g., horns) appear immediately adjacent to cold prominence material and may feed the prominence with cooling coronal plasma. Note that, even though the prominence/cavity time lags are generally inconsistent with models of nanoflare-heated ARs, this result does not rule out nanoflare heating in prominence-bearing flux tubes. In fact, for impulsive nanoflare events separated by less than a typical coronal cooling time (and localized at the footpoints), we have shown that TNE operates as it does in steadily heated flux tubes (Karpen & Antiochos 2008).

The time-lag maps contain much information, yet their complexity precludes a simple interpretation. The technique of Barnes et al. (2019), which trains a random forest classifier for incorporating the time-lag measurements and emission measures, is a promising new way to identify significant patterns. Another important future step is to analyze more sophisticated models that include many different flux tubes undergoing TNE cycles along the LOS. We plan to derive time lags for the synthetic emission maps of our multithermal simulations of TNE in a 3D sheared arcade (Luna et al. 2012). In parallel, more time-lag analyses of well-observed prominence/cavity systems are needed in order to determine whether our conclusions are valid for more than one example. The multithermal nature of the SDO/AIA channels also adds another layer of complexity. Time lags computed from spectral lines measured at the same location with time, such as with Hinode/EUV imaging spectrometer or Solar Orbiter/Spectral Imaging of the Coronal Environment sit-and-stare observations, would eliminate that source of uncertainty, though such data are sparse at present. Finally, we encourage similar time-lag studies of alternative prominence-mass formation models in order to test their applicability to observed prominences and their cavities.

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