EVIDENCE FOR EVAPORATION-INCOMPLETE CONDENSATION CYCLES
IN WARM SOLAR CORONAL LOOPS

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ABSTRACT

Quasi-constant heating at the footpoints of loops leads to evaporation and condensation cycles of the plasma: thermal non-equilibrium (TNE). This phenomenon is believed to play a role in the formation of prominences and coronal rain. However, it is often discounted as being involved in the heating of warm loops because the models do not reproduce observations. Recent simulations have shown that these inconsistencies with observations may be due to oversimplifications of the geometries of the models. In addition, our recent observations reveal that long-period intensity pulsations (several hours) are common in solar coronal loops. These periods are consistent with those expected from TNE. The aim of this paper is to derive characteristic physical properties of the plasma for some of these events to test the potential role of TNE in loop heating. We analyzed three events in detail using the six EUV coronal channels of the Solar Dynamics Observatory/Atmospheric Imaging Assembly. We performed both a differential emission measure (DEM) and a time-lag analysis, including a new method to isolate the relevant signal from the foreground and background emission. For the three events, the DEM undergoes long-period pulsations, which is a signature of periodic heating even though the loops are captured in their cooling phase, as is the bulk of the active regions. We link long-period intensity pulsations to new signatures of loop heating with strong evidence for evaporation and condensation cycles. We thus simultaneously witness widespread cooling and TNE. Finally, we discuss the implications of our new observations for both static and impulsive heating models.

Key words: Sun: corona – Sun: oscillations – Sun: UV radiation

1. INTRODUCTION

The heating mechanism(s) of coronal loops that generate million-degree plasma and maintain them at such temperatures remain unknown. Some of the main challenges are to match observational results with model predictions and to find signatures specific to some heating process. Among heating models, two different kinds of scenarios can be differentiated: impulsive heating scenarios and quasi-continuous scenarios.

Small-scale impulsive heating scenarios are referred to as “nanofores”. A nanoflare consists of a relatively low-energy impulsive event occurring through the reconnection of loop strands (e.g., Cargill & Klimchuk 1997; Klimchuk 2006; Patsourakos & Klimchuk 2006). If many of these stochastic events happen close in time in the loops, we have what is called a nanoflare storm. The nanoflare term was first proposed by Parker (1988), and since then signatures of such events have been investigated. Heating by nanofores can produce millio-degree-type loops (Guarasi et al. 2010) as well as very high temperature loops ($T > 5$ MK; Cargill 1994; Klimchuk 2006), which is one of the main strong points of heating by nanofores.

The other class of scenarios involves continuous or quasi-continuous heating concentrated at the footpoints of the loops. Numerical simulations show that in that case, the loops can undergo cycles of evaporation and condensation, a phenomenon called thermal non-equilibrium (TNE). TNE processes are known to play an important role for prominences (Antiochos & Klimchuk 1991; Karpen et al. 2006) and coronal rain (Müller et al. 2005). Coronal rain is considered to be the consequence of “catastrophic cooling” events, as seen in numerical simulations of TNE (Müller et al. 2003, 2004). Antolin et al. (2010) connect coronal rain to coronal heating mechanisms by means of a comparison between observations and MHD simulations of loops heated at the footpoints. This heating produces condensation-evaporation cycles which, in case of strong plasma condensation at the loop apex, form “blobs” of cold plasma ($T \sim 0.1$ MK). Motions of these blobs were observed by De Groof et al. (2004) with the Extreme Ultraviolet Imaging Telescope (EIT; Delaboudinière et al. 1995) on board the Solar and Heliospheric Observatory (SOHO; Domingo et al. 1995) and by Schrijver (2001) with TRACE (Handy et al. 1999).

Mok et al. (2008) consider that TNE could also be involved in the formation of coronal loops. In their simulations, heating concentrated at the footpoints leads to condensation-evaporation cycles. The temperature oscillates with a period of about 16 hr. However, the role of TNE in the heating of warm coronal loops has often been discarded, as simulations are not able to reproduce all of the observational constraints (Klimchuk et al. 2010).

Nevertheless, oversimplifications of the model geometry could explain these inconsistencies with observations. Lionello et al. (2013) present an analysis of synthetic images of an active region, obtained from 3D-hydrodynamic simulations, that seems to be consistent with observational results. In their paper, the authors analyzed emission from loops in the same way as if they were analyzing real images with diagnostics confirmed by Winebarger et al. (2014). They successfully confirmed that the loops extracted reveal seven fundamental characteristics of warm loops. In this series of papers, Mikić et al. (2013) explore the influence of the geometry of the loops and the symmetry of the heating in 1D models. Some cases lead to “catastrophic cooling” events which they called “complete” condensations. However, in other configurations,
loops remain stable to temperatures above 1 MK when only “incomplete” condensations are formed.

Recently, long-period (several hours) intensity pulsations have been found to be very common in active regions, especially in loops (Auchère et al. 2014). These pulsations are likely new observational signatures of the heating processes in coronal loops.

In this paper, we analyze in detail some long-period pulsation events found in loops to investigate the physical mechanisms involved, using data from the Atmospheric Imaging Assembly (AIA; Boerner et al. 2012; Lemen et al. 2012) on board the Solar Dynamics Observatory (SDO; Pesnell et al. 2012). This allows us to track long-period intensity pulsation events simultaneously in six coronal EUV channels: 94, 131, 171, 193, 211, and 335 Å. Compared to the previous analysis in one EIT band (Auchère et al. 2014), we can now perform physical diagnostics of the plasma. The three cases that we present here show strong evidence for cycles of evaporation and incomplete condensation. First, we present the analyzed data in Section 2.1. Then, we move to the physical analysis with a differential emission measure (DEM) diagnostic in Section 2.2 and we give evidence for widespread cooling in Section 2.3.

2. ANALYSIS OF 3 TYPICAL LOOP EVENTS

2.1. Data Sample

In order to detect long-period intensity pulsation events, we use the automatic detection algorithm developed by Auchère et al. (2014). The algorithm treats sequences of about 6 days of data at a cadence of 13 minutes, which represents about 600 images. For each sequence, a region of interest (ROI) is tracked by mapping these images into heliographic coordinates (with a resolution of 0.2° in longitude and latitude) and compensating for differential rotation. The data cube is analyzed in Fourier space (obtained by a Fourier transform of the data cube along the time axis) with respect to several criteria, the main one being a detection threshold 10σ above an estimate of the average local power. Using the database of images of EIT/SOHO in the 195 Å passband, from 1997 January to 2010 July, Auchère et al. (2014) reported 917 long-period intensity pulsation events. About half of these events have been detected.
in active regions and 50% of these have been visually associated with loops.

Here, we analyze data from AIA using the same detection algorithm. The AIA raw data are read with the routine read ado from the Interactive Data Language SolarSoftware library. We normalize the intensities by the exposure time, and so they are expressed in DNpix−1s−1f (DN: Digital Number). In order to increase the signal-to-noise ratio (S/N), we start from 4 × 4 binned images since the detected regions are large (larger than the typical area of bright points). In addition, given the detected periods, we use a cadence of 13 minutes.

The differential rotation is compensated for all passbands with the rate measured in the 195 Å passband of EIT (Horton 2003; Auchère et al. 2014), which corresponds to the average 1 MK corona. For more details about the detection algorithm, readers should refer to Auchère et al. (2014). For the Fourier analysis (Sections 2.1 and 2.2) and all of the cross-correlation computations, we resample the time series using a linear interpolation to ensure a regular cadence. We checked that the resampling does not affect the detection of long-period pulsations in the Fourier analysis, as it affects only high frequencies. See Auchère et al. (2014, Appendix A: Sources of spurious frequencies) for details about sources of spurious detections. Since the time series have about 300 images (sequences of three days of data), the 10σ detection threshold corresponds to a confidence level of 99%.

From 2010 May to 2013 December, the code detected about 2000 events. As for the EIT-based study, 50% are localized in active regions and about half of them are visually associated with loops. Since we detect some events that have also been detected with EIT (in 2010 May), we can discard definitely instrumental artefacts as the cause for these long-period intensity pulsations. Furthermore, since we do not apply any filter to the data before Fourier analysis, it is also unlikely that these events are an artefact of processing. Among the detected events, we choose to analyze three events showing a strong signal in loops, in order to investigate the underlying physical processes in detail. These three events cover a large range of periods. For the first event, the power peaks around 30.7 μHz, i.e., 9.0 hr, for the second around 49.9 μHz, i.e., 5.6 hr, and for the third around 72.9 μHz, i.e., 3.8 hr. We can thus explore the possible relationship between frequency and physical properties. The three active regions with pulsating loops are also very different with respect to their size. In addition, the three tracked active regions have moderate activity with no flares above C-class. To simplify the reading and because we reach the same conclusions with the three events, we only present event 1 in detail in the core of the text. Events 2 and 3 are presented, respectively, in Appendices A and B with the same progression.

Figure 1 represents the heliographic field of view for event 1 on 2012 June 07 at 13:47 UT in the six coronal channels of SDO/AIA. We tracked NOAA AR 1499 during 154 hr (i.e., more than 6 days), from June 03, 2012 18:00 UT to 2012 June 10 04:29 UT. In order to minimize distortion effects due to the heliographic mapping transformation5, we kept only three central days in this sequence of six days, from 2012 June 05 11:14 UT to 2012 June 08 11:16 UT. For the rest of the data

4 We assume that the structures rotate with the same velocity independently of the channel used.
5 Distortion of the structures is more important close to the limb and if the structures are tracked for a long time.

![Figure 2](image_url)  
**Figure 2.** Six light curves and the evolution of the three free parameters of the DEM model (plus $\chi^2$) from June 03, 2012 18:00 UT to 2012 June 10 04:29 UT for event 1. We have used mean intensities and mean DEM parameters in the small black contour (Figure 1). All these curves are normalized to standard deviation and offset by 5.0 along the y axis. Between DEM curves on the bottom and light curves on the top, there is an offset of 15.0 in the y axis. We restrict our analysis to the middle of the sequence (marked by the vertical dashed lines) in order to minimize distortion effects (see Section 2.1 for details). Plus signs indicate instants chosen for the four cases of DEM shape in Figure 7.**
standard deviation). The vertical dashed lines delimit the short sequence (i.e., three days) used to compute the Fourier spectra.

Figure 3 represents the corresponding Fourier power spectra, normalized to the variance $\sigma_0^2$ of these light curves (Torrence & Compo 1998). The dashed line is the estimate of the average local power. The solid line is the $10\sigma$ detection threshold. We consider only peaks of power between 18 and 110 $\mu$Hz (between 15.4 and 2.5 hr). In the 94, 131, 193, 211, and 335 Å channels there is a significant peak of power at 30.7 $\mu$Hz (9.0 hr). The normalized power at these peaks is, respectively, 12.9 $\sigma$, 10.6 $\sigma$, 17.5 $\sigma$, 22.4 $\sigma$, and 40.9 $\sigma$. In the 171 Å passband, there is no peak of normalized power above 10 $\sigma$. However, there is a 8.9 $\sigma$ peak at the frequency detected in the other bands (30.7 $\mu$Hz), plus a second 9.3 $\sigma$ peak at 46.1 $\mu$Hz (6.0 hr). This small peak at 6.0 hr also exists in the 94, 131, 211, and 335 channels with, respectively, 7.4$\sigma$, 8.3$\sigma$, 8.0$\sigma$, and 8.9$\sigma$ of normalized power. All of these peaks correspond to confidence levels greater than 90%. At 211 and 335 Å, we may also notice small peaks at 42.2 $\mu$Hz with, respectively, 7.4$\sigma$ and 9.2$\sigma$ of normalized power.

Figure 4 represents the maps of normalized power in heliographic coordinates for the six passbands at the frequency of detection (30.7 $\mu$Hz, i.e., 9.0 hr) with the same field of view in Figure 1. The normalized power is displayed in logarithmic scale with a saturation at 20$\sigma$. As for Figure 1, we displayed the contour detected at 335 Å in green and the contour that we use for analysis in black. We note that the power is localized in loops for most of the passbands. In the black contour, the normalized power is higher or equal to 7$\sigma$ on average for all of the passbands, except for 131 Å where the power is the weakest (5$\sigma$ in average). This value rises to 19$\sigma$ at 335 Å.

2.2. DEM Analysis

2.2.1. Method

We compute the DEM using the method developed in Guennou et al. (2012a, 2012b). To fit the DEM, we use the active region model developed by Guennou et al. (2013) with the six coronal EUV passbands of AIA. This parametric model is designed to represent the shape of the DEM usually observed in active regions (Warren et al. 2011; Winebarger et al. 2011). Four parameters determine the shape (as in Figure 7) of this DEM model:
1. the slope $\alpha$ of the low-temperature wing represented by a power law;
2. the peak temperature of the DEM;
3. the total emission measure (the integral of the DEM over the electron temperature $T_e$);
4. the width $\sigma$ of the high-temperature Gaussian wing. We choose to set this parameter to a fixed value of $T_0$.1 log as the high-temperature wing of the DEM is poorly constrained by AIA data.

We compute the DEM using the six channels of AIA. For this, we grouped images from the six passbands into sextuplets, allowing for a maximum non-simultaneity of $\pm 2$ minutes.

### 2.2.2. Results

For event 1, the evolution of the slope, peak temperature, emission measure, and $\chi^2$ residuals (a measure of the adequacy of the chosen model to represent the real DEM), averaged over the black contour introduced in Figure 1, is presented in Figure 2. Figure 5 represents the power spectra of these time series. The peak temperature, the emission measure, and $\chi^2$ present pulsations at the same frequency as the intensity. Actually, there are power peaks at 30.7 $\mu$Hz (9.0 hr) with, respectively, 20.1$\sigma$, 19.9$\sigma$, and 12.8$\sigma$ for these two DEM model parameters and $\chi^2$. For the slope, there is no significant power peak but a small peak (7.4$\sigma$) at 46.1 $\mu$Hz, the frequency of the secondary peaks found in the power spectra of the light curves (see Figure 3). Even if we found pulsations in $\chi^2$, the absolute value of $\chi^2$ varies between 0.2 and 1.5, which indicates a generally good fit to the DEM.

Although there is no significant power at the frequency detected in the intensity time series for the DEM slope, we found a correlation between the slope and both the emission measure and the temperature, as seen in Figure 6. The cross-correlation between the peak temperature and the emission measure is shown by a dotted line, and that between the peak temperature and the slope is shown by a solid line with a time shift between $-300$ and $+300$ minutes. These curves are computed over a duration of about 28 hr, between 62.7 hr after the beginning of the sequence (i.e., on 2012 June 06 08:42 UT) and 90 hr after the beginning of the sequence (i.e., on 2012 June 07 12:00 UT). There is a time lag of $-40$ minutes for a peak cross-correlation value of 0.7. This means that variations of the slope precede variations of the peak temperature. Between the peak temperature and the emission measure, there is also a correlation. The peak temperature is in advance of the emission measure with a time lag of 119 minutes, for a peak cross-correlation value of 0.5.

If we look at the variations of the absolute values of the DEM parameters (instead of normalizing them by their standard...
deviation, as in Figure 2), we note that the amplitude of the variations of the peak temperature is relatively small compared to the variations of the emission measure and the slope: the peak temperature varies from 2.8 MK to 3.1 MK (a relative amplitude of 11%), while there are variations from $2.03 \times 10^{27}$ cm$^{-5}$ to $2.82 \times 10^{27}$ cm$^{-5}$ for the emission measure (relative amplitude of 38%) and from 2.7 to 4.7 for the slope (relative amplitude of 71%). We note that larger temperature variations are found for event 2 and event 3 (see Appendices A and B).

Figure 7 represents four extreme cases of the shape of the DEM during the sequence. Instants chosen for the four cases are pointed out sequentially by black plus signs in Figure 2. This figure illustrates that of the three parameters of the DEM model, the slope undergoes the largest relative variations. In case 1 (in green), the DEM model is the most multithermal, as the slope reaches a minimum, $\alpha = 2.7$ (on 2012 June 05 11:14 UT), the total emission measure is $2.49 \times 10^{27}$ cm$^{-5}$, and the peak temperature is at 3.0 MK. In orange (case 2), we trace the shape of the DEM model when the peak temperature reaches a minimum at 2.8 MK. That happens on 2012 June 06 08:42 UT when the slope $\alpha = 4.0$ and the total emission measure is $2.29 \times 10^{27}$ cm$^{-5}$, and the peak temperature occurs at 2.9 MK and the total emission measure is $2.67 \times 10^{27}$ cm$^{-5}$. For case 3 (in blue), the peak temperature reaches a maximum at 3.1 MK. The slope is weaker with $\alpha = 3.0$ and the total emission measure is $2.82 \times 10^{27}$ cm$^{-5}$. This last case occurs on 2012 June 07 15:30 UT.

These results show that the DEM changes from a multithermal distribution to a more isothermal distribution and that at least the peak temperature and emission measure vary periodically. In addition, even if the normalized power found in the DEM slope Fourier spectrum is under the detection threshold, there is a clear correlation between slope and peak temperature, which is another indication that the slope also undergoes periodic variations. Therefore, from the DEM and correlation analysis we conclude that there are periodic changes in the thermal structure of the loops where we have detected long-period intensity pulsations. These periodic modifications of the thermal structure therefore must be a consequence of heating in loops, given that a cooling phase is necessarily preceded by a heating phase. This indicates that these long-period intensity pulsations are linked to loop heating.

2.3. Evidence for Widespread Cooling

2.3.1. Method

We have seen that the thermal structure of the pulsating loops undergoes periodical changes which link this phenomenon to loop heating. However, when the thermal structure of these loops evolves from a multithermal case to a more isothermal case, we do not observe heating. As has been shown by several authors, EUV loops are generally observed in their cooling phase (Warren et al. 2002; Winebarger et al. 2003; Winebarger & Warren 2005; Ugarte-Urra et al. 2006, 2009; Mulu-Moore et al. 2011). In order to show that this is the case for a large fraction of the active region in which pulsations are detected, we use the method developed in Viall and Klimchuk (2012, hereafter V&K12). V&K12 present an analysis of an active region and show that the plasma is mainly in a state of cooling, as the EUV intensity peaks first in the hotter passbands and then in the cooler passbands. By computing the time lag between several pairs of channels, V&K12 obtain the temporal succession of channels and see that the plasma is cooling down. By using 2 and 12 hr time series, V&K12 derived time lags ranging from a couple of minutes to 1.5 hr. Since the lines dominating the passbands are formed by collisions, variations of the emission measure produce simultaneous variations in the six coronal passbands. On the contrary, temperature variations
averaged over the small black contour presented in Figure 1. We used the averaged curves at 1 minute of cadence averaged over the small black contour presented in Figure 1 between 2012 June 06 08:42 UT (63 hr after the beginning of the long sequence) and 2012 June 07 12:00 UT (90 hr after the beginning of the long sequence).

Figure 6. Cross-correlation values for peak temperature/slope in solid line and peak temperature/emission measure in dotted line. We explored time shifts from −300 to 300 minutes. Time lag for each pair of DEM parameters is indicated by a black dot. We used the averaged curves at 1 minute of cadence averaged over the small black contour presented in Figure 1 between 2012 June 06 08:42 UT (63 hr after the beginning of the long sequence) and 2012 June 07 12:00 UT (90 hr after the beginning of the long sequence).

Figure 7. Four extreme cases of the shape of the DEM model (see Figure 2). In green is the shape of the DEM on 2012 June 05 11:14 UT with the minimum slope (case 1) and in red on 2012 June 06 21:42 UT with the maximum slope (case 2). In orange is the shape of the DEM on 2012 June 06 08:42 UT with the minimum peak temperature (case 2) and in blue on 2012 June 07 15:30 UT with the maximum peak temperature (case 4). The four dates corresponding to these cases are represented by plus signs in Figure 2.

Figure 8. Cross-correlation values for six pairs of AIA channels (event 1): 94–335 (red), 335–211 (blue), 211–193 (green), 335–193 (orange), 335–171 (cyan), and 171–131 (black). We used light curves at 1 minute of cadence averaged over the small black contour presented in Figure 1. We explored time shifts from −300 to 300 minutes. The time lag for each pair of channels is indicated by a colored dot.

are expected to be gradually reflected in the passbands according to the ordering of the peak temperature response of the channels: 335 Å (2.5 MK), 211 Å (2 MK), 193 Å (1.5 MK), 94 Å (1 MK and 7 MK), 171 Å (0.8 MK), and 131 Å (0.5 MK) (AIA temperature response functions; Boerner et al. 2012; Lemen et al. 2012).

2.3.2. Results

Our results in Figure 8 can be compared with Figure 4 of V&K12. As detailed below, we observe the same behavior as they did, meaning that the plasma in the small black contoured area is cooling.

Figure 8 represents the cross-correlation values for six pairs of AIA channels: 94–335, 335–211, 211–193, 335–193, 335–171, and 171–131. This calculation is made with the averaged light curves in the small black contour seen in Figure 4. Here, we choose a time cadence of 1 minute, as we expect time lags under the 13 minute cadence used previously. We explore time shifts from −300 to 300 minutes (i.e., 5 hr). Time lags are given by the peak cross-correlation value for each pair of channels.

For the 94–335 pair, we obtain a time lag of −121 minutes. This negative time lag indicates that the intensity peaks in the 335 channel before the 94 channel. The temperature response of the 94 channel has two peaks, one cooler than the 335 peak temperature and one hotter. Since 94 peaks after 335, we conclude that the plasma does not reach the temperature of the hot peak of the 94 band. The 193 channel follows the 211 channel with a time lag of 30 minutes. For pairs 335–211, 335–193, and 335–171, time lags are positive and increase gradually with 115, 144, and 153 minutes, respectively. The 171 and 131 channels show no significant time lag (−1 minute) given the time resolution.

Conclusions are more difficult to draw for the 94–335, 335–193, and 335–171 pairs, for which the peak cross-correlation values are, respectively, 0.3, 0.4, and 0.3. Peaks for 335–193 and 335–171 cross-correlations are not well separated and the time lag for 94–335 is smaller in absolute value than the time lag between 335–193 and 335–171. This can be explained because the 94, 171, and 193 channels are the most distant in time compared to the 335 channel: the emission measure is more likely to change during a longer time and the intensities in these passbands are thus more likely to be de-correlated from that in 335. Moreover, we use longer time series that in V&K12, and thus the passbands are more likely to be de-correlated. Superimposition of structures along the line of sight could also explain this effect since the background contribution may be different in the different passbands.

This analysis can be generalized to the whole active region. We build time lag maps similar to Figures 5–7 of V&K12. For each pair of channels, the time lag for each pixel is given by the peak cross-correlation value of the intensity time series. Our time lag analysis is fully consistent with the widespread cooling observed by V&K12. In particular, we observe the same ordering of channels. We note that this behavior is found in pulsating areas like in the rest of the active region.
Figure 9 represents time lag maps for the entire active region. Black areas mark regions where the peak cross-correlation value is under 0.2. In red, the time lag is positive, in blue negative, and in white we have zero time lag. The 335–211, 211–193, 335–193, and 335–171 maps are dominated by positive time lags. In the 171–131 map, we mainly observe a zero time lag. The 94–335 map reveals two different behaviors. In the core of the active region, the time lag is mainly positive, which indicates that the high temperature component of 94 dominates. On the contrary, in the outer loops (including the black contour), the time lag is mainly negative: the low temperature component of 94 dominates. In this method, we do not try to subtract the background and the foreground to isolate the loops. Thus, superimpositions of different structures along the line of sight can occur.

To conclude on the behavior of the pulsating loops with respect to the widespread cooling of the active region, we isolate the pulsating structure in Fourier space: we subtract phase maps at the detected pulsation frequency for pairs of channels, and we convert the phase difference into a time lag. Figure 10 shows the phase maps. There is no clear evidence for variation of phases along the loops. Figure 11 displays the time lag maps obtained with the method of phase maps difference. As can be seen in these maps, the phase difference is only meaningful in areas with detected pulsations; in other regions, the phases are random and so are the time lags. In this method, the pulsating loops have been isolated and the background and foreground emission, which are assumed not to be pulsating at the detected frequency, are not taken into account in the calculation of time lags. In addition, we can discern the same pattern of time lags in the pulsating loops as in Figure 9, which was obtained with the peak cross-correlation method. Using phase maps to recover time lag between channels allows us to discard the contribution of background and foreground. Moreover, we extract the signal of the pulsating loops pixel by pixel without any assumption on the shape of the structure.

We compare time lags averaged over the contour obtained with the peak cross-correlation method and with the phase difference method in Table 1. In both methods, we find similar time lags and approximately the same ordering of channels. For method 1 (cross-correlations), the time lag for 335–193 is larger than the time lag for 335–171 (145 minutes compared to 142 minutes). Therefore, the intensity peaks first in the 171 channel and then in the 193 channel. For method 2 (phase difference), the time lag for 335–193 is inferior to the time lag for 335–171 (142 minutes compared to 155 minutes). The second method gives a channel ordering that conforms more to the one predicted from a monotonic temperature decrease and
from the AIA response functions. Only the 94–335 and 171–131 pairs give a time lag that is not expected in this predicted ordering. Indeed, the absolute value of the time lag of 94–335 (114 minutes) is smaller than that of 335–211 (122 minutes), and thus the intensity peaks in 94 before that in 211. Similar ordering is found with method 1 as the time lags for 94–335 (115 minutes) and 335–211 (113 minutes) are the same given the time resolution. For the 171–131 pair, the time lag is −51 minutes when using method 2 compared to −1 minute when using method 1. Method 2 (phase difference) is limited in some passbands by the Fourier power spectrum at the detected frequency: as the normalized power is weaker for the 171 and the 131 channels, method 2 is more affected by noise, and thus less reliable for the 171–131 pair.

3. DISCUSSION

We selected three cases of long-period intensity pulsations and analyzed them in the six AIA coronal channels. These pulsations have periods of several hours, from 3.8 to 9.0 hr for the selected events. They are strongly visible in most of the passbands and are clearly matching loop structures in active regions. In each case, only some loops among those of the active regions are pulsating.

3.1. Evolution of the Thermal Structure of Pulsating Loops

Multi-spectral analysis with AIA allows us to proceed with a thermal study of these cases. The analysis of the thermal structure, i.e., the distribution and evolution of temperatures and densities, of the loops where pulsations occur reveals periodic variations. The DEM analysis also reveals high amplitude variations in the cool wing of the DEM. We link these variations to a signature of the heating of these loops. The variations in the DEM slope, which are large, can tell us about the timescale of the heating. Even though Guennou et al. (2013) have shown that the DEM slope is poorly constrained, here we interpret only the relative variations of the slope. A steep slope implies that the heated plasma does not have enough time to cool down to lower temperatures, and then that the frequency of individual heating events is high compared to the cooling time. On the contrary, when the slope is weak, a greater quantity of plasma has cooled down before being re-heated, implying a lower frequency of heating.

There are clear pulsations of the total emission measure for the three events studied. For event 1, there is a peak of normalized power above the adopted threshold (99% of confidence level) for the peak temperature. For event 2 and event 3, there are peaks of normalized power, respectively, for the peak temperature and the slope below this threshold but still at high confidence levels. These small peaks have, respectively,
97% (8.7σ) and 96% (8.4σ) confidence levels. Pulsations do not come out clearly from the Fourier analysis of the slope and the peak temperature. This can be explained by several effects impacting the DEM results.

First, we remind that the DEM analysis is made without any subtraction of the background and foreground emission because it would not be practical or meaningful given that the detected pulsations are much longer than the typical life time of loops. However background emission can be seen in Figures 1, 13, and 22, especially at 131 Å where we can clearly see the emission from the transition region. Superimposition of structures with different temperature and density conditions can partially hide the signal from the pulsating loops.

Second, the importance of the background and foreground emission can be different in the different passbands. As an illustration, for event 1 where there are no pulsations (given the 99% confidence level) for the DEM slope, the normalized pulsating power is strongest in the hotter channels (193, 211, and 335). The three other which could constrain the cool wing of the DEM may be the most affected by the background and foreground emission. On the contrary, for event 3, pulsations are exclusively visible in the cooler passbands: 94 (i.e., the cool component of 94), 131, and 171.

Third, Guennou et al. (2013) showed that the slope is poorly constrained, and thus sensitive to random variations in the light curves, which may explain why the time series of the slope is itself noisy.

To conclude, the lack of clear pulsations (given the 99% confidence level) for the DEM slope for the three events and for the DEM peak temperature for event 2 and event 3 could come from a combination of the three effects described above. In addition, even if it does not come out clearly from the Fourier spectrum, there are indications of periodic pulsations in the DEM slope from correlation analysis. Therefore, we conclude that there are oscillations in the thermal structure of these loops.

### 3.2. Widespread Cooling

The studied loops are observed in a state of cooling, as was shown using the same method as V&K12; time lag maps for six pairs of channels show widespread cooling for the three active regions, independent of the pulsating behavior of some of the loops in these active regions. To avoid the effect of the background and foreground emission, we confirm this result using a second method, extracting the pulsating component of the signal in Fourier space.
But why do we only observe cooling? The usual explanation is that the density is too small for the plasma to be detectable during the heating phase. The widespread cooling can also be a signature of heating mechanisms; V&K12 and Viall & Klimchuk (2013) interpret it as a signature of heating by nanoflare storms. In the nanoflare model, indeed, loop strands are heated (by impulsive events) and cool independently (e.g., Warren et al. 2003). In that case, the cooling time of a bundle can be much longer than the typical life time of individual loops. Nevertheless, for Lionello et al. (2013), this widespread cooling is also consistent with quasi-continuous heating, as their model can reproduce long cooling times; they can be also interpreted as superimpositions of loops cooling independently along the line of sight and are not necessarily a signature of impulsive heating mechanisms.

In the time lag maps, we do not notice differences between the pulsating loops and the rest of the active regions. The cooling phase is thus the same for the entire active region, but does not exclude different processes of heating between the pulsating loops and the rest of the active regions. The heating mechanism may or may not be the same inside and outside of the pulsating region, but there is not yet enough information to conclude.

3.3. Possible Physical Explanations for Long-period Pulsations

In order to explain the long-period pulsations seen in the coronal EUV channels and in the thermal structure of warm loops, we can put forward at least two physical explanations depending on the supposed nature of the heating. If it is impulsive, we could envisage periodic nanoflare storms, i.e., nanoflare storms with periodic changes of frequency for individual heating events, from high frequency (short time between nanoflare events) to lower frequency (more time for the plasma to cool down before being re-heated). Then, the DEM would change according to the changes in heating frequency. A change in the frequency of nanoflares might come from coupling between the motions at the footpoints and the magnetic structure of the loops.

On the other hand, quasi-continuous heating at the loop footpoints would also be a good candidate to explain our observations. This scenario drives a condensation-evaporation cycle (TNE): the plasma condenses at the top of the loops, this material falls toward the footpoints, then chromospheric material from the footpoints evaporates and fills the loops with hot plasma. Actually, even if the role of TNE was often ruled out in the heating of warm coronal loops (Klimchuk et al. 2010), we find that the long-period intensity pulsations observed in loops are consistent with condensation-evaporation cycles. Figure 12 represents the time lag between the peak temperature and the emission measure for the entire field of view for event 1. This map is built by subtracting the phase maps of the DEM peak temperature and of the emission measure at the main frequency detected for event 1. This allows us to obtain the time lag map between the peak temperature and the emission measure for only the periodic component of these parameters. Therefore, pulsating loops at the detected frequency are isolated in Fourier space. This map shows a time lag of 123 minutes on average in the selected contour, which is what we already found in Figure 6 without Fourier filtering. This corresponds to a de-phasing of 81°. This result is to be compared with Figure 6 in Mikić et al. (2013) where they compare the evolution of the temperature and density at the apex of a symmetric simulated loop with a nonuniform cross-section area and nonuniform heating. The temperature and density of their simulation have cyclic variations with a period of 5.0 hr, which is on the order of the periods that we observed. The density curves have a delay of about 1.5 hr compared to the temperature curve. This implies that the temperature variations always precede the density variations with a de-phasing of approximately 108°. For this simulation, the authors note the development of incomplete condensation cycles localized near the loop legs and a temperature at the loop apex that remains above 1 MK. The observed and modeled dephasings are comparable, as far as Mikić et al. (2013) use the density and we only have access to the total emission measure.

Even if long-period intensity pulsations are connected to heating processes in loops, these pulsations only occur in some loops of the studied active regions and not in all of the active regions. In other words, why do we not have long-period intensity pulsations in all loops? This could be due to the background and foreground emission as developed earlier in the text. Intrinsic properties of loops could also explain why some loops do not show this kind of pulsation. For Mikić et al. (2013), the plasma response to a steady heating mainly concentrated at the loop footpoints depends on the loop geometry: the uniformity and the symmetry of the cross-sectional area, the symmetry of the loop profile, and the symmetry of the heating profile with different heating functions. The geometry of the loops and of the heating could lead to different condensation strengths which they call “incomplete” and “complete” condensation. This connects TNE processes to both coronal rain and the heating of warm loops.

The wide distribution of observed periods could be due to inherent properties of the loops. In Auchère et al. (2014) a possible relation between the length of the loops and the period of the pulsations was discussed. Here we also note that for these three events, the longer the period of pulsations, the larger the detection area. It remains to be confirmed whether or not the loop length is a good candidate to explain the different periods observed in pulsating loops.

4. SUMMARY AND CONCLUSIONS

Auchère et al. (2014) have shown that long-period intensity pulsations are a common phenomenon in coronal loops. Using the same detection algorithm, we have detected many other cases in the six coronal channels of AIA. Among these, we selected three events detected in three different active regions. The observed pulsations have, respectively, periods of 9.0, 5.6, and 3.8 hr. The normalized power maps of the three studied active regions clearly show that these pulsations are strongly localized in some, but not all loops of active regions. Thus, either the occurrence of these cycles depends on specific loop properties or some events could be masked by the background and foreground emission.

We investigate the physical properties underlying these pulsations. First, by means of a DEM analysis using the active region DEM model from Guennou et al. (2013). We note periodic variations of the shape of the DEM during the sequences studied. The thermal structure of these loops changes periodically from a strong multithermal structure to a more isothermal structure. We link these variations to a signature of heating mechanisms. Moreover, using the same method as in V&K12, we note that the studied active regions are mainly
seen in their cooling phase. This is confirmed by extracting in Fourier space the loops at the detected frequency, allowing us to remove contributions from the background and foreground emission. Although this widespread cooling could be linked to nanoflare heating, it does not inevitably imply impulsive heating. In fact, Lionello et al. (2013) shows, by means of 3D-hydrodynamic simulations, that TNE processes could also be consistent with widespread cooling. Our observations bring a new element to this debate. Since these pulsations appear to be common in coronal loops and are linked, as we suggest, to the heating of the plasma, then any model of loop heating must be able to reproduce these new observations.

The SDO/AIA images are available courtesy of NASA/SDO and the AIA science teams. This work made extensive use of the AIA archive at MEDOC, http://medoc-sdo.ias.u-psud.fr.

APPENDIX A

EVENT 2

A.1 Data Sample

Figure 13 shows images of a second example of pulsating loops with a long period on 2012 December 30 at 21:28 UT. For event 2, the NOAA AR 11637 was tracked from 2012 December 28 10:00 UT to 2013 January 02 18:42 UT (i.e.,

Figure 12. Time lag map obtained from differences of phase maps of the peak temperature and of the emission measure. We explored time shifts from −300 to 300 minutes. The green contour is the detected contour and the black contour is the contour manually selected.

Figure 13. Same as Figure 1 for event 2 on 2012 December 30 at 21:28 UT. This event is localized in NOAA AR 11637.
As for event 1, we focused on the three middle days of this sequence, from 2012 December 29 14:26 UT to 2013 January 01 14:29 UT (i.e., 72 hr). The contour in green is the contour detected in the 171 Å channel centered at 342.5° longitude and 20.5° latitude with an area of 12.9 heliographic square degrees (1495 Mm²). We manually selected a small contour (in black) included in the detected contour to obtain the time series presented in Figure 14.

We display the normalized Fourier spectra in Figure 15. In the 94, 131, 171, 193, and 335 Å channels there is a significant peak of power at 49.9 μHz (5.6 hr). The normalized powers are, respectively, 16.7σ, 13.5σ, 19.9σ, 19.3σ, and 25.5σ. Even if there is no peak above 10σ in 211, we can note a small peak with a normalized power of 9.6σ at 49.9 μHz. At 94 and 193 Å, there is also a small peak at 42.2 μHz with, respectively, 8.1σ and 11.7σ of normalized power.

Figure 16 represents the maps of normalized power for event 2, at the detection frequency (49.9 μHz, i.e., 5.6 hr). Loops of NOAA AR 11637 are clearly seen in these maps for all of the passbands. The averaged normalized power is larger than 10σ for all of the passbands, except 211 Å (7σ). Loops of NOAA AR 11640, a second active region around 320° in longitude and 30° in latitude, have also normalized power above 10σ. The automatic algorithm does not detect these loops with the set of arbitrary thresholds. This suggests that

Figure 14. Same as Figure 2 for event 2 from 2012 December 28 10:00 UT to 2013 January 02 18:42 UT.

Figure 15. Fourier power spectra for event 2, same as Figure 3.
Figure 16. Same as Figure 4 with the same scale. Maps of normalized power at the frequency of detection (49.9 \( \mu \)Hz, i.e., 5.6 hr) for event 2. The black contour, included in the detected contour at 171 Å (in green), is manually selected for detailed time series.

Figure 17. Fourier power spectra for the three parameters of the DEM model for event 2, same as Figure 5.
more of these events are probably not detected by our code. Loops of this second active region (emerging at the beginning of the sequence) seem to have almost the same length, which could be why they have the same frequency of pulsations (see Section 3.3).

A.2 DEM Analysis

The evolution of the mean DEM slope, peak temperature, emission measure, and $\chi^2$ in the selected contour of event 2 is presented in Figure 14. Figure 17 represents the power spectra of these parameters. For the emission measure there is a peak power at 49.9 $\mu$Hz, i.e., 5.6 hr. The peak at the time is 15.0$\sigma$. If we look under the detection threshold at 49.9 $\mu$Hz, there is a peak with a power of 8.0$\sigma$ for $\chi^2$, but its variations from 0.3 to 1.8 indicates a good fit. For the peak temperature, there is a small peak (8.7$\sigma$) at 46.1 $\mu$Hz. For the slope there is no significant peak of power.

Even if the power is weak for the peak temperature and there are no pulsations found with the Fourier analysis for the slope, we found a clear correlation between the slope and both the peak temperature and the emission measure, between 97 hr and 120 hr after the beginning of the full sequence. In Figure 18, we plot the cross-correlation values for DEM peak temperature versus emission measure and slope. We find a clear correlation between the peak temperature and the emission measure (cross-correlation value of 0.66) and anti-correlation between the peak temperature and the slope (cross-correlation value of −0.74). We can conclude that there are indications that the slope varies periodically with periods of hours, and thus that the thermal structure of the studied loops undergoes periodical changes.

The amplitudes of the variations of the DEM parameters are larger than for event 1: there are variations from 2.2 to 3.2 MK (a relative amplitude of 45%) for peak temperature, from $3.2 \times 10^{27}$ to $6.4 \times 10^{27}$ cm$^{-5}$ for emission measure (a relative amplitude of 97%), and from 1.7 to 4.8 for the slope (a relative amplitude of 176%).

A.3 Evidence for Widespread Cooling

Figure 19 represents the time lag maps made with the peak cross-correlation values. Figure 20 represents the phase maps at Figure 18. Same as Figure 6. We used the averaged curves at 1 minute of cadence averaged over the small black contour presented in Figure 1 between 2013 January 03 22:28 UT (97 hr after the beginning of the long sequence) and 2013 January 04 21:28 UT (120 hr after the beginning of the long sequence).
Figure 20. Same as Figure 10 for event 2 with the same scale.

Figure 21. Same as Figure 11 for event 2 with the same scale.
Table 1
Comparison of Time Lag Values Between the Two Methods: Peak Cross-correlation Values and Differences of Phase

| Pairs of Channels | Time lag (minutes) From Cross-correlations (Figure 9) | Time lag (minutes) From Differences of Phase Figure (11) |
|-------------------|--------------------------------------------------|--------------------------------------------------|
| 335–211           | 113                                              | 122                                              |
| 211–193           | 26                                               | 20                                               |
| 335–193           | 145                                              | 142                                              |
| 94–335            | −115                                             | −114                                             |
| 335–171           | 142                                              | 155                                              |
| 171–131           | −1                                               | −51                                              |

Note. These are the averaged time lag in minutes in the black contour.

Table 2
Same as Table 1 for Event 2

| Pairs of Channels | Time lag (minutes) From Cross-correlations (Figure 19) | Time lag (minutes) From Differences of Phase Figure (21) |
|-------------------|--------------------------------------------------|--------------------------------------------------|
| 335–211           | 35                                               | 37                                               |
| 211–193           | 25                                               | 31                                               |
| 335–193           | 80                                               | 68                                               |
| 94–335            | −71                                              | −68                                              |
| 335–171           | 69                                               | 73                                               |
| 171–131           | 1                                                | −4                                               |

**Figure 22.** Same as Figure 1 for event 3 on 2011 August 09 12:12 UT. This event is localized in NOAA AR 11268.
49.9 μHz. For the two active regions included in the field of view, the phases are constant along the loops (as seen in Figure 10 for event 1) but there is a gradient of phases across the bundle of loops. Further analysis is needed to explain this gradient. Figure 21 shows the differences of phase maps for six pairs of channels. We included the detected contour in green and the contour manually selected in black. On most of the field of view the plasma is in a state of cooling, for both Figures 19 and 21: time lags are mainly positive for the 335–211, 211–193, 335–211, 335–193, and 335–171 pairs, mainly negative for 94–335 and equal to zero for 171–131. The mean time lags in the black contour can be compared in Table 2.

![Graph showing phase maps and time lags.]

**Figure 23.** Same as Figure 2 for event 3 from 2011 August 07 04:00 UT to 2011 August 13 05:49 UT.

**Table 3**

| Pairs of Channels | Time lag (minutes) From Cross-correlations (Figure 28) | Time lag (minutes) From Differences of Phase Figure (30) |
|-------------------|------------------------------------------------------|------------------------------------------------------|
| 335–211           | 26                                                   | 4                                                   |
| 211–193           | 14                                                   | 29                                                   |
| 335–193           | 50                                                   | 33                                                   |
| 94–335            | −36                                                  | −33                                                  |
| 335–171           | 76                                                   | 42                                                   |
| 171–131           | 0                                                    | −1                                                   |

**Figure 24.** Fourier power spectra for event 3, same as Figure 3.
Figure 25. Same as Figure 4 with the same scale. Maps of normalized power at the frequency of detection (72.9 $\mu$Hz, i.e., 3.8 hr) for event 3. The black contour, included in the detected contour at 94 Å (in green), is the contour manually selected for detailed time series.

Figure 26. Fourier power spectra for the three parameters of the DEM model for event 3, same as Figure 5.
Using the cross-correlation method, intensity peaks in the following channel order: 335, 211, 171, and 131, 94, and 193. Using the phase difference method, the order becomes 335, 211, 193, 94, 171, and 131, which is the order expected from the expected temperature evolution and from the AIA response functions. This second method is better in this case (event 2) because the power is high enough in all the passbands at the detected frequency. However, for pairs like 94–335 and 335–193, time lags are almost equal. We note that these time lags are smaller than the time lags found for event 1 (about half). These smaller time lags are likely due to the smaller loop length (smaller detection area) for event 2.

APPENDIX B

EVENT 3

B.1 Data Sample

Figure 22 shows images of a last example, event 3, on 2011 August 09 12:12 UT. For this event, the ROI (45° in longitude) was tracked from 2011 August 07 04:00 UT to 2011 August 13 05:49 UT (i.e., about 146 hr), and we select the three middle days of this sequence, from 2011 August 08 16:53 UT to 2011 August 11, 16:56 UT (i.e., 72 hr). Pulsations are detected in loops located above the core of NOAA AR 11268. The detected contour at 94 Å (in green) is centered on 218.0° of longitude and 21.4° of latitude with an area of 6.3 heliographic square degrees (730 Mm²). In Figure 23, we represent the average light curves in the selected contour (in black). The corresponding Fourier spectra in Figure 24 show strong signal in the 94, 131, and 171 Å channels. Pulsations are detected in these three bands at 72.9 μHz (3.8 hr) with, respectively, a power of 27.4σ, 18.4σ, and 14.7σ above the estimated background spectrum. At 211 Å and 335 Å there is no significant power peak, but at 193 Å there is a small peak at 8.2σ.
Figure 29. Same as Figure 10 for event 3 with the same scale.

Figure 30. Same as Figure 11 for event 3 with the same scale.
In this last channel, there is also a small peak (7.0σ) at 88.3 μHz.

Figure 25 represents the maps of normalized power for event 3, at the detection frequency (72.9 μHz, i.e., 3.8 hr). The normalized power in the 94, 131, and 171 Å channels is higher than 14σ on average inside the black contour. For the other passbands, the normalized power is weaker, but the power maps also display loops near the core of the active region.

### B.2 DEM Analysis

The evolution of the mean DEM slope, peak temperature, emission measure, and χ^2 in the selected contour for event 3 is presented in Figure 23.

Figure 26 represents the power spectra of these parameters. Pulsations are detected for the emission measure and χ^2 at 72.9 μHz, the same frequency of detected pulsations in the light curves. The normalized power at these peaks are, respectively, 11.0σ and 10.1σ. If we look under the detection threshold, there is a small peak of power for the the slope (8.4σ). Between 40 hr and 70 hr after the beginning of the large sequence, we found a clear correlation (0.78 of peak cross-correlation value) between the peak temperature and the emission measure as seen in Figure 27.

The amplitudes of the variations of the DEM parameters are larger than for event 1 and event 2; there are variations from 1.9 to 3.8 MK (a relative amplitude of 99%) for the peak temperature, from 3.0 × 10^27 to 8.9 × 10^27 cm^-5 for the emission measure (a relative amplitude of 196%), and from 1.4 to 3.3 for the slope (a relative amplitude of 144%). These strong variations of both the peak temperature and the total emission measure are observed in the core of an active region where any type of activity is in general expected to be the highest.

### B.3 Evidence for Widespread Cooling

The time lags maps in Figure 28 (made with the peak cross-correlation method) highlight a widespread cooling in this active region. Figure 29 represents the phase maps. The phases are constant along the loops. Maps produced with the second method (phase differences), shown in Figure 30, lead to the same conclusion of widespread cooling. The delay presented in Table 3 for both methods, show a better succession of channels with the second method: with the first method we have the 335, 211, 94, 193, 171, and 131 orders, whereas with the second we obtain 335, 211, 193, and 94, 171, and 131, which is the ordering expected for the AIA channels. However for this event and for both methods, results are noisy for some pairs of channels. Indeed, for the first method, the peak cross-correlation values are poor for some pairs in the black contour (Figure 28) and the time lags for 335–193 and 335–171 are the most affected. The second method suffers from the lack of strong power in the 335, 211, and 193 channels. For event 3, we observe time lags smaller than for event 1 and event 2, that can be explained by the probably smaller loop length (smaller detection area) for event 3.

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