PLASMA SLOSHING IN PULSE-HEATED SOLAR AND STELLAR CORONAL LOOPS

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ABSTRACT

There is evidence that coronal heating is highly intermittent, and flares are the high energy extreme. The properties of the heat pulses are difficult to constrain. Here, hydrodynamic loop modeling shows that several large amplitude oscillations (~20% in density) are triggered in flare light curves if the duration of the heat pulse is shorter than the sound crossing time of the flaring loop. The reason for this is that the plasma does not have enough time to reach pressure equilibrium during heating, and traveling pressure fronts develop. The period is a few minutes for typical solar coronal loops, dictated by the sound crossing time in the decay phase. The long period and large amplitude make these oscillations different from typical magnetohydrodynamic (MHD) waves. This diagnostic can be applied both to observations of solar and stellar flares and to future observations of non-flaring loops at high resolution.

Key words: stars: coronae – stars: flare – Sun: activity – Sun: corona – Sun: flares

1. INTRODUCTION

One fundamental question about coronal heating is whether the energy released in coronal loops is gradual or impulsive (Klimchuk 2006; Parnell & De Moortel 2012; Reale 2014). There is increasing evidence in the time series that in active regions, the heating may be highly irregular (e.g., Sakamoto et al. 2008, 2009; Vekstein 2009; Terzo et al. 2011; Viall & Klimchuk 2011, 2012; Ugarte-Urra & Warren 2014; Tajiriouve et al. 2016a, 2016b). This question spawns additional inquiries, for instance, whether the heat pulses are frequent or not with respect to the plasma cooling time (e.g., Warren et al. 2011). This is very difficult to constrain, because coronal loops are likely to be structured into thin strands, where the heating is released through a storm of small-scale pulses. The single heating episodes can hardly be resolved up to date. Within the framework of intermittent heating, an important issue to consider is the duration of the heat pulses, because it links directly to the basic mechanisms of magnetic energy conversion, e.g., reconnection. For instance, recent work has suggested that the pulses are preferentially short (≤1 minute, Testa et al. 2014; Tajirrouze et al. 2016b).

Even in flares, the duration of the pulses is difficult to diagnose, because the efficient heat conduction thermalizes the whole flaring loop in few seconds, canceling all heating signatures in the EUV and soft X-rays. Some diagnostics about the features of the heating come from hard X-rays, which track the emission from non-thermal electron beams. However, it is debated whether the electron beams are entirely responsible for the flare heating or if they co-exist with other mechanisms excited by fast magnetic reconnection, e.g., the dissipation of current sheets (e.g., Battaglia et al. 2015).

Here, we propose a way to diagnose the duration of the heating release in brightening coronal loops. Coronal loops can be described as closed magnetic tubes where the plasma is confined and moves and transports energy along the field lines. If the heat pulse is short, strong pressure waves are triggered inside the magnetic flux tube. Because the temperature is very uniform along the loop due to the efficient thermal conduction,
Figure 1. Evolution of the temperature (solid), pressure (dotted), and density (dashed) at the loop apex for the pulse duration $t_H = 60$ s (a) and $t_H = 120$ s (b). The values are normalized to 16.4 MK, 51 dyn cm$^{-2}$, and $1.67 \times 10^{10}$ cm$^{-3}$, respectively, for panel (a) and 16.4 MK, 78 dyn cm$^{-2}$, and $2.44 \times 10^{10}$ cm$^{-3}$ for panel (b).

fluctuations. It is a separate function of time and space. For basic time dependence, we use a pulse function that is 1 for the duration of the pulse and 0 at any other time. We also conducted tests using a triangular pulse, which had equal rise and decrease times. For space dependence, we assume heating is uniformly distributed along the loop. As a check for generality, we also test a twin heat pulse deposited at both loop footpoints.

The initial atmosphere is the usual hydrostatic corona linked to the chromosphere through a steep transition. The chromosphere is taken from standard models (Vernazza et al. 1981) and is kept at equilibrium by a temperature-dependent heating function (Peres et al. 1982).

For reference conditions, we consider a loop half-length (the loop is symmetric) $L = 25,000$ km; we also conducted tests for a loop four times longer ($L = 10^5$ km). The initial loop atmosphere is relatively cool and tenuous. For the shorter loop, the density at the apex is $n_0 \approx 10^8$ cm$^{-3}$, the pressure $p_0 \approx 0.02$ dyn cm$^{-2}$, and the temperature $T_0 \approx 6 \times 10^2$ K and is kept constant by a coronal heating rate $H_0 = 2.4 \times 10^{-5}$ erg cm$^{-3}$s$^{-1}$. For testing, we have also considered an initially warmer and denser atmosphere ($n_0 \approx 1.5 \times 10^9$ cm$^{-3}$, $p_0 \approx 0.8$ dy cm$^{-2}$, $T_0 \approx 1.9 \times 10^6$ K, and $H_0 = 1.2 \times 10^{-3}$ erg cm$^{-3}$s$^{-1}$).

In this equilibrium atmosphere, we inject a heat pulse. As a reference case, we consider such a pulse intensity to bring the loop temporarily to a temperature above 10 MK. This mimics heating typical both of medium class flares and of the hottest strands in a non-flaring multi-fibril active region loop (e.g., Reale et al. 2011; Testa & Reale 2012; Tajiriouze et al. 2016b). For the shorter loop, the heating rate is $H = 1$ erg cm$^{-3}$s$^{-1}$ ($H = 0.05$ erg cm$^{-3}$s$^{-1}$ for the longer one), which brings the loop to a maximum temperature $T \approx 16$ MK. For generality, we have also considered a heating rate 100 times lower ($H = 0.01$ erg cm$^{-3}$s$^{-1}$), which brings the loop to a temperature of about 4 MK.

In this study, the key parameter is the pulse duration. We have found that the reference timescale to trigger the plasma sloshing is the loop return (isothermal) sound crossing time:

$$\tau_s = \frac{2L}{c_s} \approx \frac{50L_0}{\sqrt{T_1}}$$

where $c_s$ is the sound speed, $L_0$ is the loop half-length in units of $10^9$ cm, and $T_1$ is the maximum loop temperature in units of $10^7$ K. For a maximum temperature of 16 MK, we obtain $\tau_s \sim 100$ s. We bracket this timescale with two pulse durations, $t_H = 60$ s and $t_H = 120$ s. We test the 4× longer loop with a short pulse duration of $t_H = 300$ s and the 4× cooler loop with $t_H = 180$ s.

Using these settings, the hydrodynamic equations have been solved by means of the Palermo-Harvard numerical code, with adaptive mesh refinement (Peres et al. 1982; Betta & Testa 1997).

3. THE SIMULATIONS

In the following, we will describe in detail the results for two basic simulations: those with the reference loop half-length (uniformly distributed) heating rate and initial atmosphere, and with the pulse durations either $t_H = 60$ s or $t_H = 120$ s.

Since the heat pulse is much stronger than the equilibrium heating rate, the temperature rises throughout the loop to the flare value within a few seconds because of the very efficient thermal conduction. The pressure increases as well, and the overpressure drives an explosive expansion of the chromosphere upwards in the corona (chromospheric evaporation). After the heat pulse stops, the plasma rapidly cools down, again because of thermal conduction, while the density continues to increase for some time, because the dynamic timescale is longer than the conduction timescale. Eventually, when the conduction cooling is replaced by the radiative cooling (e.g., Cargill 1994), the plasma begins to drain and the density decreases. This evolution is well-known from standard loop modeling (e.g., Bradshaw & Cargill 2006; Reale & Orlando 2008; Cargill & Bradshaw 2013; Bradshaw & Klimchuk 2015). Here, we focus on the different modulation of this evolution determined by the different pulse durations.
Figure 2. Evolution of the pressure along (half of) the loop for the pulse duration $t_H = 60\,\text{s}$ (a) and $t_H = 120\,\text{s}$ (b). To emphasize the presence of moving fronts, the pressure is normalized to the mean coronal value at each time, and the gray scale is between 80% and 120% of the mean value.

Figure 1 shows the evolution of the temperature, pressure, and density at the loop apex for the two different pulse durations. For the first 60 s, the evolution is, of course, identical. Then it differentiates, and the temperature drops for the short pulse duration and stays high longer in the other case. During the cooling, the evolution is radically different, because strong oscillations are present for the short pulse duration and are not present for the long one. These modulate the evolution and are best visible in the pressure and density. From Fourier analysis, the period of the most powerful component is $\sim 150\,\text{s}$, slightly increasing with time, and five full oscillations are clearly visible in the time range up to 1000 s (shown in the figure), after which the density has dropped to approximately one-third of the maximum value. Such clear oscillations are, instead, not visible for $t_H = 120\,\text{s}$. The oscillations have an $\sim 20\%$ amplitude in the density and are damped with time.

They are the signature (at the apex) of a twin density (or pressure) front that sloshes up and down between the footpoint and the apex of the loop. Figure 2(a) ($t_H = 60\,\text{s}$) shows this front very clearly in the form of bright zig-zagging bands. The front is more contrasted at the beginning because of the sudden heating from a cool condition, and then it slowly fades. For $t_H = 120\,\text{s}$ (Figure 2(b)), we only see the initial bright pressure front, but this is already promptly damped on the initial way down and is very faint afterwards.

The reasons for this different evolution can be understood from Figure 3. In both cases, we see the initial steep evaporation front coming up (rightward in the figure) from the chromosphere. Afterwards, for $t_H = 60\,\text{s}$ (Figure 3(a)), the pressure continues to increase at the loop apex (right side), because plasma accumulates there. However, the pressure does not increase low in the loop (left side), and as soon as the heat pulse stops, it suddenly drops. This depression makes the upper steep pressure front travel backwards (downwards) along the loop (from right to left in the figure). The pressure drops as the temperature drops because of conduction cooling. As seen in Figure 1, the temperature decreases by more than 30% in less than one minute, which is much less than $\tau_s$ necessary to equalize the pressure. For $t_H = 120\,\text{s}$ (Figure 3(b)), the heat pulse lasts long enough to sustain the plasma and to equalize the pressure along the whole loop. Therefore, the critical process is whether the pressure equilibrium is or is not reached along the loop, which explains why the sound crossing time is the key parameter.

We confirmed that we find very similar results, i.e., significant plasma sloshing when the heat pulse duration is shorter than $\tau_s$, for the longer loop, the denser initial atmosphere, the heat pulses deposited at the loop footpoints, and the weaker heat pulse. For the triangular pulse, we find that sloshing is still present for a 120 s pulse duration and is cancelled for a pulse that is twice as long. Therefore, if the pulse is more gradual than one that is square, the threshold $t_H$ still holds using an “equivalent duration” that shrinks the triangular pulse to an equivalent square pulse. Overall, this is a very general finding. It is worthwhile to remark that: (a) the pulse duration should be compared to $\tau_s$ estimated at the temperature maximum (or more correctly, at the temperature of the pressure maximum), because the sloshing is triggered by the initial pressure imbalance; (b) the period of the oscillations is essentially the time taken by the pressure/density front to travel back and forth along the loop; because, during this time, the plasma has considerably cooled down, the period is quite longer than $\tau_s$. For instance, in Figure 1 the initial period of 150 s corresponds to a sound crossing time for a temperature of $\sim 7\,\text{MK}$. The period (slightly) increases with time, because the wave speed decreases in the cooling medium.

As a final step, we explore whether this effect would be visible in the observations. We synthesize the emission as it would be observed in the 94 Å channel by the Atmospheric Imaging Assembly (AIA Lemen et al. 2012) on board the Solar Dynamics Observatory (SDO;Pesnell et al. 2012). We choose this channel because it is sensitive to the emission from 5 to 10 MK plasma, but the results are general for any band or spectral line that is most sensitive to the emitting plasma. We assume that the plasma is optically thin and use the standard channel response function taken from the SolarSoftWare. On the relatively long evolution times of our loop simulations we can assume ionization equilibrium (Reale & Orlando 2008). The cross-section area is 1 pixel ($0.6\times0.6$). Figure 4 shows the light curves obtained from segments 1000 km long at three different positions along the loop for both heat pulse durations.

Although, overall, we see a fast rise and slower decay typical of flare events, the light curves from the short pulse simulation are strikingly different from those of the long pulse one. They are highly irregular, with periodic modulations that resemble those in the density (Figure 1). The fluctuations are even amplified, because the emission depends on the square of the density. Larger fluctuations are present at the footpoint (the emission is more intense there because the density is higher due to gravity stratification). The light curves from the long pulse simulation are instead smooth and do not show significant fluctuations. The small late bump ($t \sim 900\,\text{s}$)—also present in the short pulse light curves—is due to the second sensitivity peak around 1 MK in the 94 Å channel (Foster & Testa 2011). Figure 4 shows that the fluctuations driven by the plasma sloshing are detectable in the light curves.
4. DISCUSSION

We have shown that short heat pulses can excite large amplitude wavefronts of plasma confined in coronal loops. The critical timescale is the return sound crossing time (or the sound crossing time along the entire loop length) at the temperature peak. If the pulse duration is shorter than this timescale, then there is not enough time to equalize the pressure in the initial transient, and plasma sloshing is triggered back and forth between the apex and the footpoints. Since the efficient thermal conduction keeps the temperature very uniform along the loop, the pressure fronts are mostly density fronts and determine strong fluctuations in the emission that can be detected in the light curves taken in the appropriate bands.

We remark that we are modeling plasma flowing freely along the flux tube and that there is no direct interaction with the magnetic field, except for confinement and channeling. The excited waves are, therefore, purely hydrodynamic waves in a compressible plasma, different from low-order MHD modes, such as sausage or kink modes.

The assumption of closed loops symmetric with respect to the apex makes the model evolution particularly clear and well-behaved. This scenario is an acceptable simplification, because we might expect that magnetic reconnection triggers heat pulses deposited symmetrically at both loop footpoints. Also, if the heat pulses are spread in the coronal part of the loop, the efficient thermal conduction would level out the temperature along the whole loop. Regardless, twin density fronts would arise from the chromosphere at both footpoints and with a very small time difference, and they would hit against each other high in the loop, determining the initial accumulation that triggers the sloshing. This may not occur exactly at the loop apex, so, if the evolution is not totally symmetric, we might expect more irregular quasi-periodic patterns. In addition, loops that are not symmetric could have very different gravitational stratifications in each leg, leading to more irregular patterns.
The amplitude of the density waves is large and even larger in the plasma emission because of the dependence on the square of the density. These are not standing waves nor are they acoustic harmonic oscillations inside the loop (Selwa et al. 2005), and they have been customarily found in previous loop modeling (e.g., Reale et al. 2012; Bradshaw & Cargill 2013).

We might expect to detect them easily in the light curves, whenever present. Unlike typical magnetoacoustic waves, their period is relatively large (minutes, or more for longer loops) and, therefore, easy to identify. They may be best detected if the heating is released almost all at once across a loop, to have a coherent evolution, as in proper flares. Also, the large amplitude makes them different from typical MHD waves.

Another point is interesting to remark upon. A general decay time has been found for plasma flaring in single loops (Serio et al. 1991; Reale 2007, 2014):

\[ \tau_d = 120 \frac{L_0}{\sqrt{T^2}}. \]  

(2)

This decay timescales exactly as the sound crossing time (1), i.e., the period of the waves scales as the decay time of the flare. Since the decay is typically the longest part of a flare, the implication is that, whatever the flare duration, any flare light curve will contain a similar number of major oscillations (not many, typically around five).

In the end, we propose that periodic oscillations detected in the light curves of solar and stellar flares are often due to plasma sloshing as modeled in the present study and that their presence depends on the duration of the flare heating related to the flaring loop length (whereas the dependence on the temperature is relatively weak). This, becomes a new way to identify pulsed heating and to constrain its duration. This does not seem to be so frequent in solar flares, probably because the length of the loops that brighten initially is often quite small. In spite of the smaller signal to noise ratio, it is, instead, more frequent in stellar flares, which can occur in giant magnetic channels (López-Santiago et al. 2016).

We can extend this result to flares of any scale, in particular, to small scales (nano-flares). We could expect to detect oscillations in light curves from non-flaring coronal loops in active regions, as observed, for instance, by SDO/AIA. This is not typically the case (e.g., Sakamoto et al. 2008, 2009; Viall & Klimchuk 2011; Tajfirooz et al. 2016a, 2016b). However, short heat pulses may still be present in the framework of multi-stranded pulse-heated loops. Tajfirooz et al. (2016b) find that short pulses better match the observed light curves and Tajfirooz et al. (2016a) show that, even if there are strong oscillations in the single light curves, they are washed out when they are mixed up along the line of sight across a loop with a multitude of independently heated strands. We might hope to detect such oscillations even in non-flaring loops with the appropriate resolution of next generation instruments.

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