Observations and Implications of Large-Amplitude Longitudinal Oscillations in a Solar Filament

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Introduction: Large-amplitude longitudinal (LAL) oscillations

Observational LAL features

Observation	Amp. ($km\, s^{-1}$)	Period (min)	Damping Time (min)	Trigger
Jing et al. (2003)	92	80	210 (2.6 P)	Nearby sub-flare
Jing et al. (2006)	50	160	600 (3.8 P)	Nearby C-Class flare
Jing et al. (2006)	30	150	—	Nearby microflare
Jing et al. (2006)	100	100	—	—
Vršnak et al. (2007)	51	50	115 (2.3 P)	Nearby sub-flare
Zhang et al. (2012)	40	52	133 (2.6 P)	Nearby C-Class flare
Li & Zhang (2012)	30-60	44-67	—	Nearby flare activity

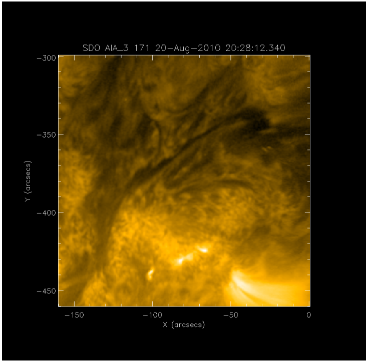
- Large-amplitude longitudinal (LAL) oscillations are characterized by motion of the plasma with velocities $> 20\ km\, s^{-1}$; the displacements are almost parallel to the filament axis.
- According to current models and measurements of filament magnetic fields, the LAL motions are along the magnetic field.
- The LAL oscillation periods are about 1 hour and damp in a few cycles (strong damping).
- The accelerations involved are huge $\sim 100\ \mathrm{ms}^{-2}$ comparable to the Sun surface gravity ($g_0 = 274\ \mathrm{m\ s}^{-2}$).
- Apparently the trigger is an energetic event close to the filament.
- The capabilities of current telescopes allow monitoring of the full Sun's. We have found many LAL oscillations indicating that these are very common. As I will show, this makes LAL oscillations good candidates to obtain information on prominences.

Open questions:

1. What is the restoring force of these oscillations? The prominence has a large mass that moves back and forth with large accelerations.
   - Magnetic origin: the restoring force is related to the magnetic tension. The associated displacements are perpendicular to the local magnetic field. However, LAL oscillations are mainly along the local magnetic field.
   - Gas-pressure origin: the restoring force is the gas pressure (slow MHD mode). However, the temperatures necessary to accelerate the prominence threads to observed values are on the order of 10 Million Kelvin. Although these temperatures are not observed, they could be present in the triggering associated with the flare.
   - Gravitational origin: the projection of the gravity along the dipped magnetic field is the restoring force. This is consistent with most filament models, and with the fact that the LAL accelerations are comparable to the solar gravity.
2. What is the damping mechanism? The oscillating prominence has a large kinetic energy,
   - The damping mechanism is poorly understood. Several damping mechanisms have been suggested but not rigorously tested, e.g., energy leakage by the emission of sound waves (Kleczek & Kuperus 1969) or some form of dissipation (Tripathi et al. 2009; Oliver 2009).
3. What initiates the oscillation? A lot of energy is necessary to perturb the prominences.
   - In all of the observations the trigger is associated with some energetic event.

Observations: 2010-08-20 LAL event

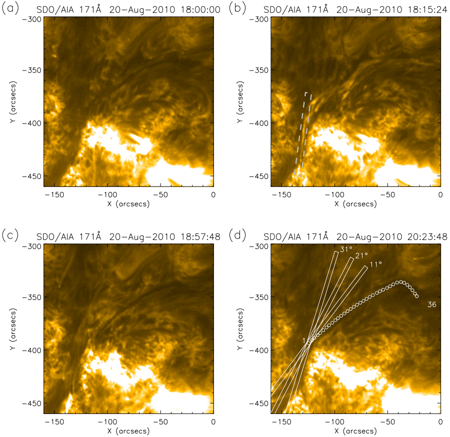
- On 20 August 2010 an energetic disturbance triggered large-amplitude longitudinal oscillations in a nearby filament.
- This event is observed in Hα and the EUV bandpasses of the SDO/AIA.
- The LAL oscillations are very clear in the AIA 171Å filter: the cool plasma is seen by absorption surrounded by bright emission (PCTR).



- At the beginning (15:00 UT) the motions resemble the well-known counterstreaming Zirker et al. (1998)
- Around 18:10 UT a narrow collimated flow of plasma appears near the south end of the filament. The maximum Jet speed is of 95 $km\ s^{-1}$ (see section).
- By 19:00 UT the outflow from the jet source has ceased and the filament oscillates with a very coherent, large-scale motion until the end of the temporal sequence.

Observations: Analysis

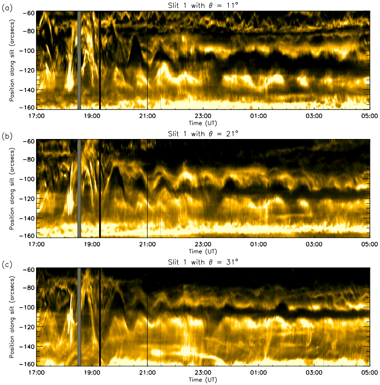
- We have analyzed the motions along the filament axis.
- It is difficult to follow the motion of individual features, thus we place slits and create time-distance diagrams for every position.



- We have place 36 slits along the filament spine. The filament spine consist in basically to straight lines.

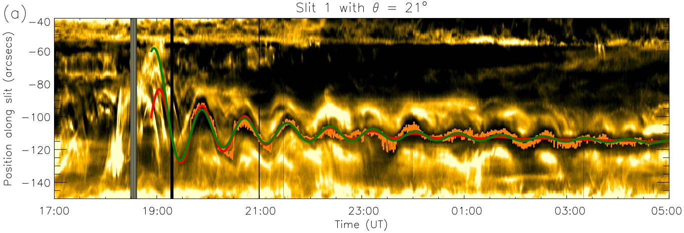
Observations: Analysis

- Although the oscillation is clear in all three following panels, the oscillatory pattern in the time-distance diagrams depends strongly on this angle.
- We select the slit angles with the best oscillatory pattern: a clear dark band sandwiched between 2 distinct bright emission regions, the longest possible time interval over which the oscillations were measurable, and the maximum possible displacement amplitude (see movie).



- We assume that in the best time-distance diagram the orientation of the slit coincides with the direction of the motion of the threads, and the orientation of the threads (both thread-ends move completely in phase).

- After creating time-distance diagrams for all 36 positions along the filament, we found that the filament only oscillated at positions 1-6, 33, and 34, while the remainder of the filament remained stationary.



- The coronal heating located at filament footpoints produces a constant accretion of mass by the prominence threads (Antiochos & Klimchuk, 1991). According to our model of Luna & Karpen (2012) the mass accretion produces a damping of the oscillations. The temporal dependence of the oscillation is a Bessel function instead of a exponentially decreasing sinusoid.
- We have fitted both functions: the exponentially decaying sinusoid (constant mass) and a zero-oder Bessel function (mass accretion):

$$s(t) = s_0 + A_{\mathrm{Exp}} e^{-(t-t_0)/\tau} \cos\left[\omega(t-t_0)+\phi_0\right] + d_0(t-t_0)\,, \quad (1)$$

$$s(t) = s_0 + A_{\mathrm{Bes}} J_0\left[\omega(t-t_0)+\psi_0\right] e^{-(t-t_0)/\tau_w} + d_0(t-t_0) \quad (2)$$

Observations: Analysis

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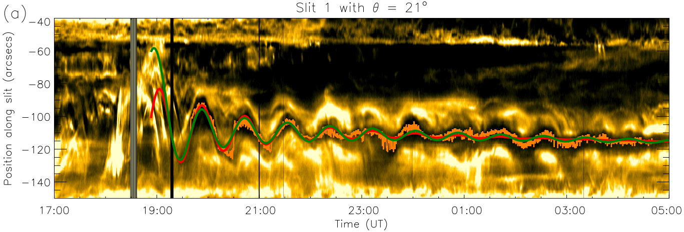
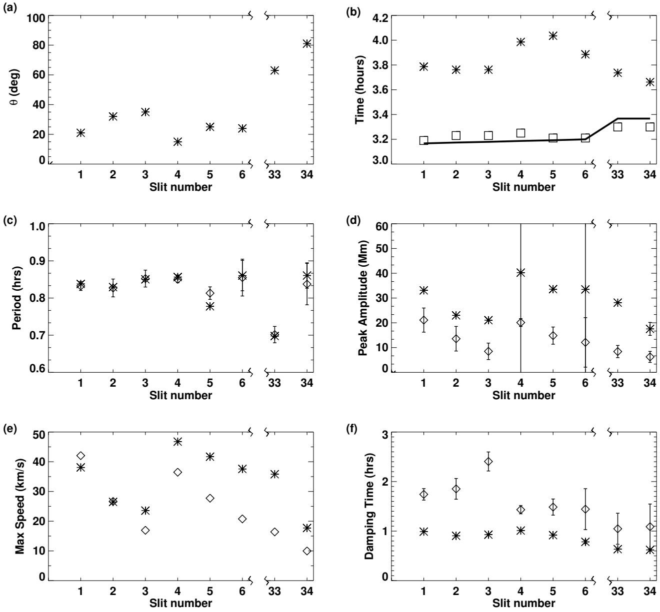


- The orange dots are the position of the minimal emission in 171Å, which we use to fit the two functions. The red curve is the exponentially decaying sinusoid and the green curve is the Bessel function.
- Visually the two functional fits to the data are very good. Both have the same number of free parameters, so their relative goodness can be assessed by comparing the standard deviation σ^2 of each function (Asensio-Ramos, 2012). Both fits have similar, reduced σ^2 values, indicating that the fits are equally good.
- However, the modified Bessel function provides better fits to the initial plasma dynamics and damping, and to the longevity of the oscillations.

Results of the fits



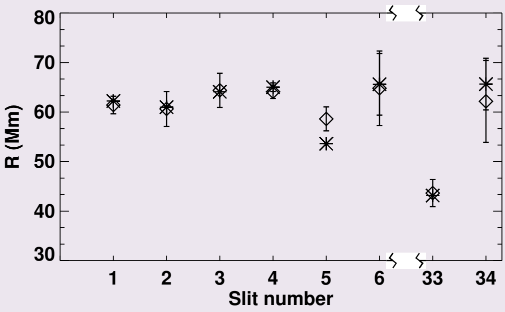
Asterisks → Bessel, and diamonds → Exponentially decaying fit.

The theoretical model

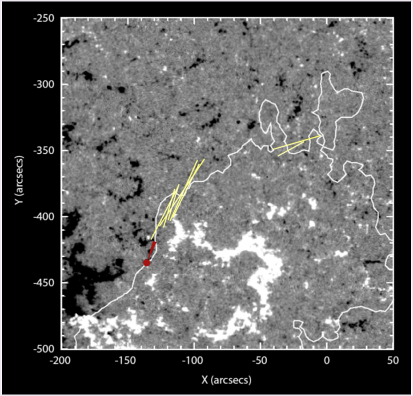
- The restoring force is a combination of the solar gravity projected along the magnetic field and the pressure gradients. In Luna, Díaz, & Karpen (2012) we found that
$$\omega^2 = \omega_g^2 + \omega_{slow}^2 \approx \omega_g^2 = \frac{g_0}{R} \ ,$$
where R is the radius of curvature of the dipped field lines. The period of the oscillation is independent of the mass of the threads or the magnetic field. It is only dependent of a geometrical factor of the dipped field lines.
- In Luna & Karpen (2012) we found that the continuous mass accretion by the threads is the responsible of the strong damping of the LAL oscillations. The mass accretion rate, α, is on the phase of the Bessel function, $\psi_0 = \omega m_0/\alpha$.
- The magnetic field tension should at least support the thread masses. Thus, this condition give us a minimal value of the magnetic field:

$$B[\mathrm{G}] \geq 26 \left(\frac{n_\mathrm{e}}{10^{11}\ \mathrm{cm}^{-3}}\right)^{1/2} P[\mathrm{hours}] \ .$$

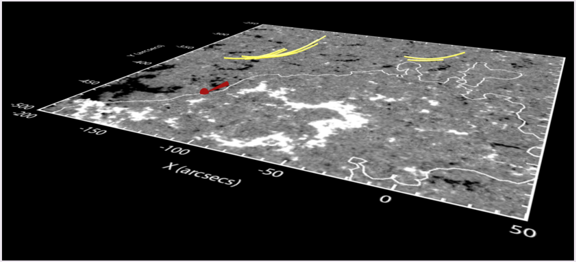
The radius of curvature along the filament



The radius of curvature along the filament



The radius of curvature along the filament



- We can infer partially the geometry of the filament channel structure.
- The dips have a radius of curvature of approximately 60 Mm.

The mass accretion rate

- The phase of the Bessel function contains the information of the mass accretion rate, $\psi_0 = \omega m_0/\alpha$.
- From the fits we measure ψ_0 and infer the initial mass, $m_0 = 1.27 m_{\rm p} n_{\rm e} \pi r^2 l$. The mass of the thread is proportional to the length of the thread, l.
- $m_0(kg) = (4 \pm 3) \times 10^6 \; l(\mathrm{Mm})$.
- The thread length is estimated to be the slit-aligned length of the central dark (absorption) region of the time-distance diagrams of the LAL oscillations.
- With this mass estimate and the measurement of l, the mass accretion rate is estimated to be

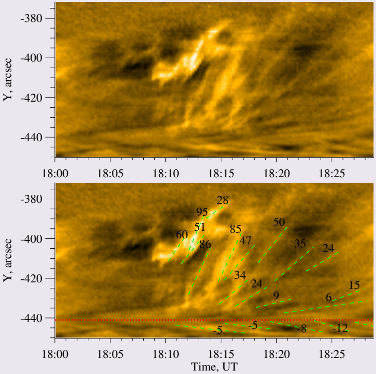
$$\alpha = (36 \pm 27) \; \times 10^6 \, \mathrm{kg \; hr}^{-1} \, , \tag{1}$$

which is consistent with the theoretical values predicted by our thermal nonequilibrium model with steady heating Karpen et al. (2006) and Luna et al. (2012).

The oscillation trigger: the Jet

The Jet

- Around 18:10 UT very collimated plasma flows start to emanate from $\{x \sim -135'', y \sim -440''\}$, ejecting plasma toward the SE end of the filament situated $\sim 70''$ ($\sim$51 Mm) away from the source.
- This jet is clearly visible in emission in several AIA EUV filters (171 Å, 193 Å, 131 Å, 304 Å, 211 Å, and 94 Å), indicating that the multi-thermal flow includes very hot plasma.



- The flow speed reaches $\sim 95\ \mathrm{km\ s^{-1}}$ in the first episode, and decreases significantly in subsequent episodes.
- Applying the same analysis method to the AIA 193 Å, 335 Å and 304 Å images gives very similar time-distance. We conclude that the flow speed is independent of temperature.
- The initiation of the oscillation agrees with the arrival time of a perturbation propagating with a speed of $95\ \mathrm{km\ s^{-1}}$ (parallel picture).

The oscillation trigger: the Jet

Flare energy estimation

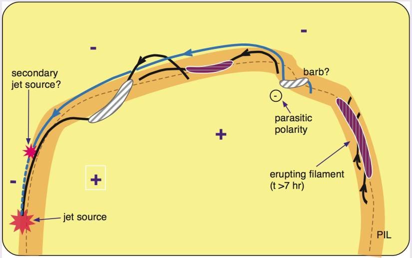
- We estimate the energy released to the filament by the jet event by computing the kinetic energy of the oscillations: $E = 1/2 M_{\rm osc} v^2$, where $M_{\rm osc}$ is the oscillating thread mass and v is the averaged velocity amplitude of the oscillation ($\sim 30\ \mathrm{km\ s^{-1}}$).
- Because only 8 of 36 slit positions exhibit periodic motions, we estimate that only $8/36$ ($\sim$ 22%) of the total filament mass oscillates:

$$E = 10^{26} \left(\frac{M}{10^{14} g} \right) \ \mathrm{erg}\ . \tag{2}$$

- For a typical prominence mass $M = 10^{12} - 10^{15}\ g$ (Labrosse et al., 2010), the energy of the oscillating filament is predicted to be $E = 10^{24} - 10^{27}\ \mathrm{erg}$.
- The energy transferred to the filament by the jet is an unknown fraction of the total energy released by the initiating event, however, so E places a lower limit on the trigger energy. Zhang et al. (2013) carried out numerical experiments generating LAL oscillations by impulsive heating at one footpoint of a loop, and found that the energy of the thread oscillations is only 4% of the impulsive energy release.
- In our case the initiating event manifests several key characteristics of a microflare, most notably the presence of a jet, the duration, and the energy range (see reviews by Benz, 2008; Shibata, 2011).

LAL oscillation event overview

Cartoon and overview



- The chirality of the filament should be sinistral, in agreement with Wang et al (2013a) who found that the barbs are left bearing.
- The NW substructure traversed by slits 28-36 is most likely a barb pointing to a small, negative parasitic polarity within the mainly positive region.
- A reconnection process takes place close to PIL at the northern side. The resulting jet plasma flows along the filament channel field lines at a projected speed of $\sim 95\ \mathrm{km\ s^{-1}}$.
- These field lines only connect with some parts of the filament, such that the flow reaches the SE part and the NW barb.
- Threads in these regions are pushed by the hot flows, then oscillate in the dips. The restoring force of the oscillations is the projected gravity along the dips, as our model predicts.
- Continuous, localized coronal heating produces evaporation of chromospheric plasma that accretes onto the already formed filament threads. This mass accretion is responsible for the initial strong damping of the oscillations.

Conclusions and Future work

Conclusions

The study of the large-amplitude longitudinal oscillations reveals easily characteristics of the prominence structure. The LAL seismology is a powerful tool.

Future Work and Questions

- Seems that the LAL oscillations are very frequent (I have nice movies!).
- Seems that small flares occur close to the filament and frequently buffeting the threads.
- Is the triggering related with the life of the prominence?
- The counter streaming and solar tornadoes show similar periodicities as the LAL oscillations. Have those oscillations a similar nature?
- How do the threads are triggered? Seems that there are twisting/untwisting motions of the field lines before the threads are “pushed” (more movies!).