Transverse oscillations of solar filaments with SDO/AIA observations in 304 Å passband

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Abstract

Solar filaments are dark, dense and cold formations surrounded by a hot corona (Gibson, 2018; Zhou et al., 2020). Observations with high spatial resolution show the fine structure of the filaments, which are composed of individual threads (Lin et al., 2005). Temperature: ~ 10^4 K, density: 10^{11}-10^{12} cm^{-3} (Awasthi, Liu, and Wang, 2019).
Numerous studies of quasi-periodic oscillations of filaments have shown the presence of periods from several minutes to several hours (Tripathi, Isobe, and Jain, 2009; Arregui, Oliver, and Ballester, 2018; Luna et al., 2018, Zapior et al., 2019; Luna et al., 2018; Li et al., 2018;). Their interpretation is related to the propagation of MHD waves.

Modern results of numerical MHD simulations of wave propagation in solar filaments and prominences indicate the existence of transverse oscillations in it with characteristic periods of ~ 4-30 minutes. (Jelínek et al., 2020; Adrover-Gonzalez and Terradas, 2020;). But the results of numerical simulations strongly depend on the given magnetic configuration of a filament, changes in which affect the variations in physical parameters and → on the range of oscillation periods (Zhou et al., 2018). *Therefore, the refinement of the magnetic structure, physical parameters, and dynamic properties of solar filaments play an important role in understanding the issues of their structure and formation.*

The aim of this work is:
- to reveal the parameters of transverse oscillations of solar filaments with periods of more than 5 minutes, according to observations in the 304 Å passband;
- to propose the interpretation of the results in the framework of MHD.

Data analysis results

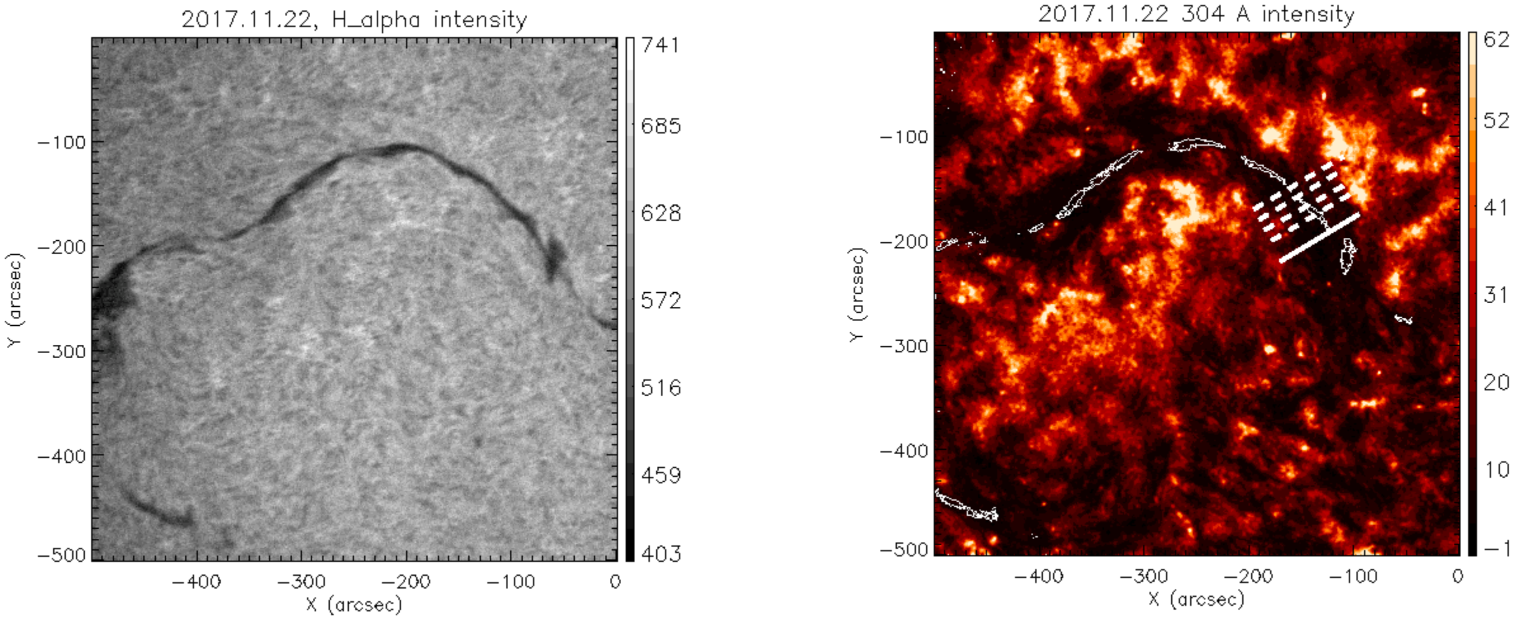

Figure.1. Left: image of the solar filament in the Hα line (Kanzelhoe observatory).
Right: image of the same filament in the 304 Å passband (Solar Dynamics Observatory, Atmospheric Imaging Assembly). The filament in the Hα is represented here by a white contour at the 50% level.
To analyze the transverse oscillations of the filament, 5 slits have been produced (solid and dashed lines). The length of the slits is ~ 100”. The distance between the slits is 10".

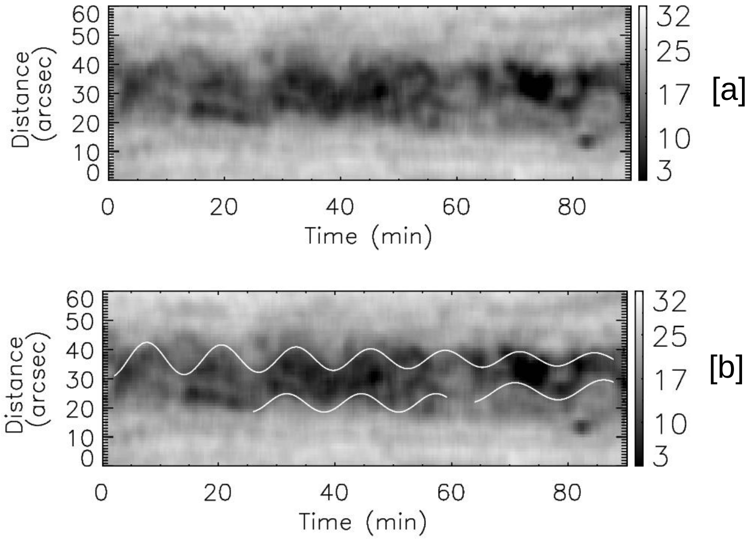

Figure 2. Example of a time-distance diagram (the first slit in Fig.1, right) [a]. White curves represent the result of the fit of transverse oscillations. Fitting: Markwardt (2009) [b].

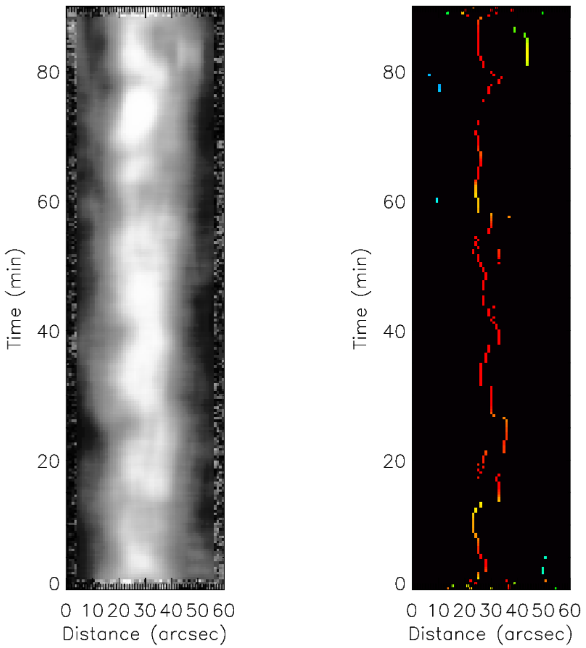

Figure.3. Illustration of a technique of a local peaks detecting.
Left: time-distance diagram (colors inverted).
Right: a set of local peaks.

$$f(t) = A_0 + A_1 \cdot sin(\frac{2\pi t}{A_2} - A_3) \cdot exp(-A_5 t) + tA_4,$$

Analysis of filament variations: this method is discussed in the works of Morton et al. (2012, 2013) and Weberg et al. (2018). This method identifies peaks in the intensity on a time-distance diagram, according to specified criteria. Each peak is a local minimum / maximum of intensity defined in a box of a given size. The gradient of the slopes on either side of the local minimum is used to define the peak. We limited the intensity value inside the box for each diagram based on intensity variations only at the edges of the filament. The error of the peaks localization is 0.5 pixels.

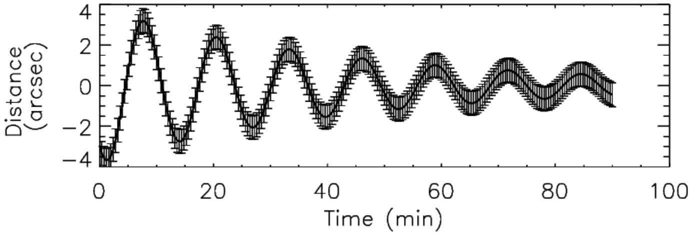

Figure.4. Fitting errors (1σ, Bevington &Robinson 1992, Markwardt 2009).

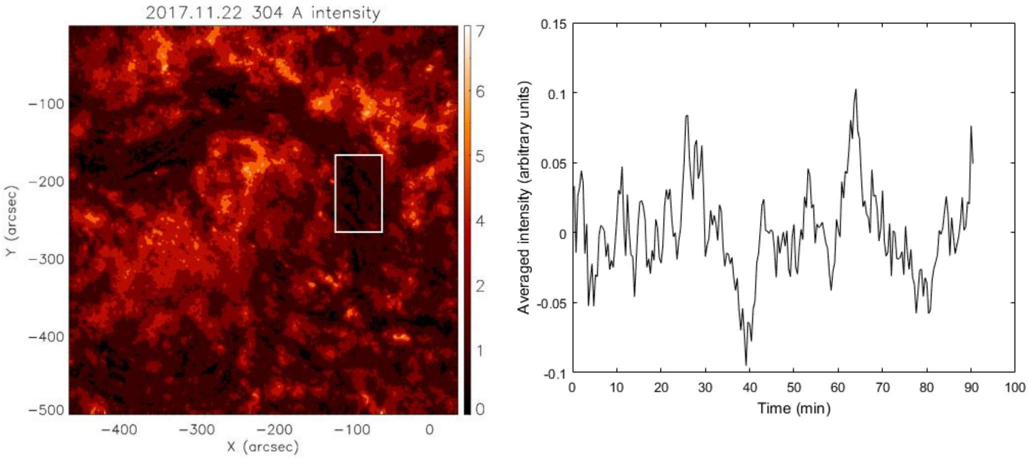

Figure 5. We also analyzed the averaged intensity variations of the filament inside the chosen area. Left: image of the filament in the 304 Å passband (square root of intensity). The area in which the average intensity was considered is highlighted with a white box. Right: Time series of average intensity variations (trend subtracted). The average intensity is 11 counts. Amplitude of intensity variations: 0.05.

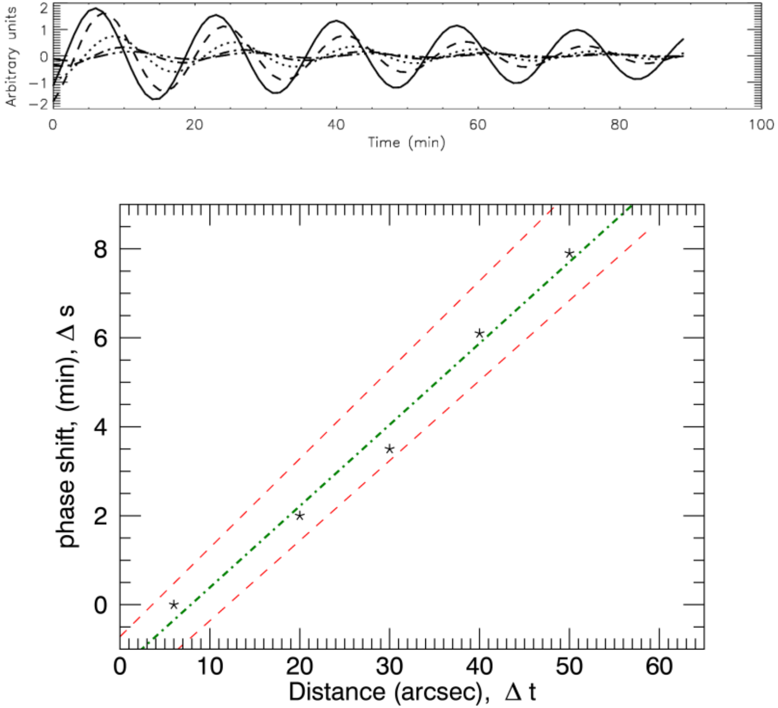

Figure 6. Top: Fitting results. These time series testify in favor of a weakly damped wave that propagates from one part of the filament to another. The phase shift between the rows was determined by the cross-correlation method. Bottom: Phase shift versus distance between the slits.

Interpretation

The structure of solar filaments and prominences observed with high spatial resolution (Hiller et al. 2013) shows the presence of individual threads filled with cold plasma, usually two orders of magnitude denser and colder than the surrounding corona. They are usually assumed to delineate magnetic flux tubes. It can be assumed that the observed transverse displacements are associated with the propagation of kink modes through these thin magnetic tubes. First of all, it is necessary to explain the observed small amplitudes of the intensity variations with respect to the transverse displacements. Solving the system of equations of ideal MHD in a cylindrical coordinate system, assuming that the perturbation is $\propto f(r) exp(-i\omega t + kz + \varphi)$ and using standard notation, one can obtain the following relationship between the perturbed density $\delta\rho$ and radial velocity v_r for kink modes (Stepanov et al. 2005):

$$\frac{\delta\rho}{\rho} = -ir\frac{\omega(\omega^2 - k^2 v_A^2)}{(v_A^2 + c_s^2)(\omega^2 - k^2 c_T^2)}\frac{\partial}{\partial r}(r\delta v_r), \qquad (1)$$

$$\omega^2 = k^2\frac{\rho v_A^2 + \rho_e v_{Ae}^2}{\rho + \rho_e}, \quad c_T^2 = \frac{v_A^2 c_s^2}{v_A^2 + c_s^2},$$

Radial shift is $\xi_r = iv_r/\omega$ and $\delta v_r = v_0 kr/2$, where $v_0 = \mathrm{const}$ (Tsap and Kopylova 2001), assuming $\beta \approx c_s^2/v_A^2 \ll 1$ and $\rho \gg \rho_e$ we obtain:

$$\frac{\delta\rho}{\rho} = -2\pi(kr)\frac{\xi_r}{\lambda}. \qquad (2)$$

Equation (2) assumes that variations of density and cross-sectional area occur in antiphase for kink waves, which are fast MHD modes (Van Doorsselaere, Nakariakov, and Verwichte, 2008).

Thus, taking into account that for an optically thick source the intensity $\delta I \propto \delta\rho$ (Tsap, Stepanov, Kopylova 2016) and after averaging over the cross section with radius a, from Eq. (2) we obtain

$$\left|\frac{\delta I}{I}\right| = \pi(ka)\frac{\xi_r(a)}{\lambda} = \pi^2\frac{d}{\lambda}\frac{\xi_r(a)}{\lambda}, \quad (3)$$

where *d=2a*

Phase difference for a propagating harmonic wave at different times is equal to

$$\Delta\phi = 2\pi\frac{\Delta t}{T}, \quad (4)$$

Where *Δt* – time shift, *T* – period of oscillations. Wavelength is:

$$\lambda = 2\pi\frac{\Delta s}{\Delta\phi} = T\frac{\Delta s}{\Delta t}, \quad (5)$$

where *Δs* – distance between the slits.
From observations: the radial shift is 3 x 10^3 km, *d* = 300 km, *T* = 17 min, $\lambda \approx 120 \times 10^3$ km,
$\Delta s/\Delta t \approx 117$ m/s, from equations (3) and (5):

$$|\delta I/I| \approx 2 \times 10^{-4}$$

According to equation (5), the phase velocity of the wave is:

$$v_{ph} = \frac{\lambda}{T} = \frac{\Delta s}{\Delta t}. \quad (6)$$

Taking into account that $B_e \approx B$ and equation (1):

$$v_{ph}^2 = \left(\frac{\omega}{k}\right)^2 \approx \frac{B^2 + B_e^2}{4\pi\rho} \approx 2v_A^2. \quad (7)$$

Thus, we could estimate the Alfvén velocity inside the flux tube as:

$$v_A \approx \frac{v_{ph}}{\sqrt{2}} = \frac{1}{\sqrt{2}}\frac{\Delta s}{\Delta t}.$$

From observations: $v_A \approx 83$ km/s. Magnetic field inside the flux tube:
$B \approx 4.5 \times 10^{-12} v_A \sqrt{n} = 37 - 118$ G.

where $n = 10^{11} - 10^{12}$ cm^{-3}

Conclusions

The dynamics of a quiet solar filament is analyzed based on observations in the 304 Å passband (AIA / SDO). Time-distance diagrams made it possible to reveal quasiperiodic displacements of the filament edges. We assumed that the oscillations can be explained by the propagation of kink modes in thin magnetic tubes.
The Alfvén velocity V_A ~ 83 km s^{-1} and the magnetic field B ~ 37-118 G were estimated by using the presented diagnostics. It should be emphasized that the dispersion equation used by us is also applicable to thin magnetic ropes.

Lin et al. (2009), Montes et al. (2019), have produced an analysis of individual threads of prominences. The authors obtained the periods of transverse oscillations of threads in the range from 2 to 4 minutes with amplitudes from 400 to 1800 km. Using a similar technique, the values of the Alfvén velocity were estimated in the range of 12-44 km s^{-1} and the magnetic field 0.9-6 G. The significant difference, first of all, for magnetic fields can be explained by the small value n = 10^{10} cm^{-3}, adopted by these authors for the threads density.