How flux rope heating affects solar prominence formation: oscillations analysis

N. Brughmans[1*], R. Keppens[1†]

[1] *Centre for mathematical Plasma Astrophysics, KU Leuven, Belgium*

Abstract

We performed 2.5D *ab-initio* simulations of prominence formation in a solar coronal domain where we deformed an arcade to a flux rope setting. Our simulations introduce a 3D-inspired heating model that locally and dynamically reduces the heating rate in the flux rope hosting the prominence. This results in the formation of a multitude of condensations throughout the flux rope. Here, we analyse the 'natural' oscillations that arise when these condensations fall down and collect in magnetic dips, and compare their periods to the analytical pendulum model predictions.

Introduction

Prominences are large structures suspended in the solar corona that are considerably cooler ($< 10{,}000$ K) and denser than the surrounding atmosphere, which is at temperatures around 1 MK. In simulations of prominence formation, one specifies a background coronal heating term that initially provides thermal balance against optically thin radiative losses to keep the atmosphere at this temperature. As no self-consistent model for coronal heating exists as of yet, the adopted heating model varies from a steady heating source falling exponentially with height, to a time-dependent parameterisation depending on *e.g.* the magnetic field strength, density, or field line length.

In our recent work [2], we describe a novel heating model for 2D flux rope simulations which takes into account the complex 3D structure of a flux rope, consisting of twisted magnetic field lines. A dynamically adjusted reduction of the background heating term is applied inside the flux rope, simulating the decreased effectiveness of thermal conduction in transporting energy along these long field lines. This enhances the effectiveness of radiative losses, rendering all of the flux rope susceptible to thermal instability. As a result, most of the material in the flux rope cools down and collects in the concave-upwards dipped field after condensing. As the condensations fall from as high as the top of the flux rope, they perform damped oscillations along the field lines (to which they are bound in this low plasma-β regime) because of their

*: nicolas.brughmans@kuleuven.be
†: rony.keppens@kuleuven.be

finite kinetic energy. These oscillations, which are in the 2D plane in our simulations, are the subject of this study.

Oscillations resulting from prominence formation are a known phenomenon that may explain counter-streaming motions observed in prominences [1]. However, it is unclear whether the oscillations we get spontaneously when the blobs gather in the dips - which do not require an external perturbation - have actually been observed. The small oscillation amplitudes (and periods) found in this work could make it challenging for observations, even though they may be an underestimate due to the 2D projected views analysed here.

Methods

We perform 2.5D grid-adaptive simulations of prominence formation using MPI-AMRVAC [4] on a domain of 24 by 25 Mm as described in [2, 3]. All relevant details can be found in these papers, but for completeness we mention that we solve the full MHD equations, including magnetic resistivity ($\eta = 0.002$ in dimensionless value), thermal conduction (anisotropic Spitzer conductivity), optically thin radiative losses and background heating [2].

The oscillation analysis was performed on both a run with finite magnetic resistivity ($\eta = 0.002$) and a run with resistivity disabled, restarted at $t = 6475$ s, after flux rope formation. This allows us to observe the influence of mass slippage over the field lines on the measured oscillations. Similar to the analysis by [5], we trace a collection of 21 field lines starting at fixed positions in the upper half of the flux rope at approximately 60 instances in the time interval $6475 - 10,940$ s. These field lines have dips between approximately $4 - 12$ Mm. It is assumed that the upper part of the flux rope is relatively unperturbed and hence approximately the same field lines are traced throughout the simulation. For every field line, the parallel velocity is calculated according to $v_{\|} = \frac{\vec{v}\cdot\vec{B}}{|\vec{B}|}$, where only the 2D components of these vectors are used. Identifying the prominence material on a field line by having $T < 25,000$ K and $\rho > 1.171 \times 10^{14}$ g/cm^3, oscillations can be analysed by considering the variation of the parallel velocity of the centre of mass of the prominence:

$$v_{\|,\mathrm{CM}} = \frac{\sum_s v_{\|}(s)\rho(s)}{\sum_s \rho(s)}. \tag{1}$$

The pendulum model predicts the periods of the oscillation periods as linear perturbations with a restoring force provided by the magnetic tension. The predicted periods are given by

$$P = \frac{P_0}{\sqrt{1+\frac{R}{R_\odot}}}, \qquad P_0 = 2\pi\sqrt{\frac{R}{g_0}}, \tag{2}$$

where R is the local radius of curvature of the magnetic field (here taken for the 2D poloidal field), $R_\odot = 696.34$ Mm is the solar radius and $g_0 = 274$ m/s^2 is the solar gravitational acceleration [6]. The expression for P above provides a correction for varying gravitational acceleration $g(y) = g_\odot \frac{R_\odot^2}{(R_\odot+y)^2}$, as is present in our simulations. To calculate the radius of curvature, we find the average curvature in a portion of the field line around the prominence at every time. For every field line, *the* curvature is then defined as the temporal average of these spatial averages. Curvature is calculated at every location using forward differences,

$$\vec{\kappa} = \frac{\vec{b}(s+\Delta s) - \vec{b}(s)}{\Delta s}, \quad (3)$$

where $\vec{b}$ is the unit vector along the magnetic field and s is the coordinate along the magnetic field. Again, since the motion is restricted to the plane, we only consider 2D vector components, although the MHD simulation is 2.5D.

Results

The velocity of the prominence mass centre along each tracked field line is shown on Fig. 1.

First, there is a clear variation of oscillation amplitudes with height. In general, the amplitudes are larger for the lower-lying field lines as a result of the material falling down from higher up in the flux rope. This does not hold for the lowest three field lines, because the condensations on them form relatively close to their dip. The magnitudes of the velocity variations are of the order of 2 – 10 km/s, and hence we are dealing with small amplitude oscillations [1].

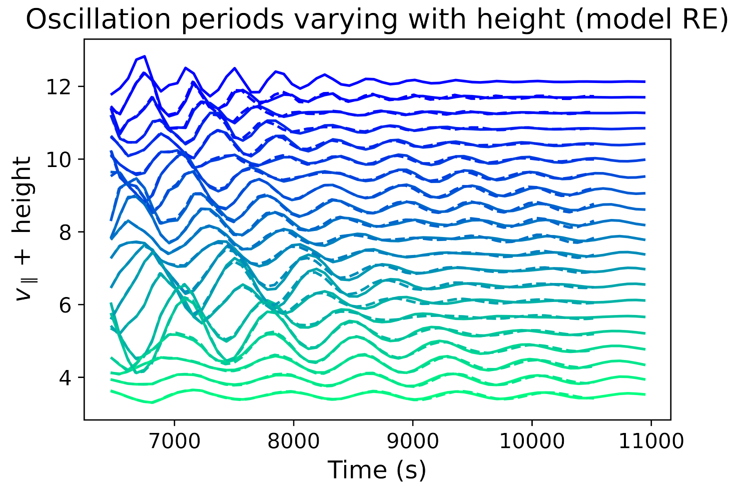

Figure 1: *Variation in field-aligned velocity of the centre of prominence mass along several field lines. The velocity amplitudes have been scaled for clarity. Field lines are ranked according to approximate height of their dips and coloured accordingly. Simulations with magnetic resistivity* $\eta = 0.002$ *(solid) and* $\eta = 0$ *(dashed).*

Second, there is a clear dependence of the oscillation periods on height of the field line dip, as evidenced by the apparent diagonal lines connecting the oscillation maxima on different field lines on Fig. 1. As is to be expected, the oscillation periods are shorter closer to the flux rope centre, since the field lines on which the material is located are shorter. Additionally, a notable difference arises between runs where magnetic resistivity was included or not: the occurrence of resistive mass slippage over the field lines has the effect that the periods tend to shorten, which could be a consequence of material leaving field lines, changing the momentum of the oscillating material.

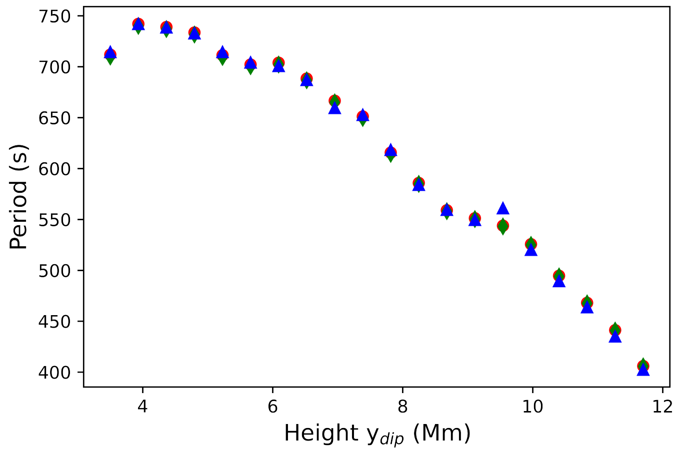

Figure 2: *Overview of the measured and theoretical periods as a function of height of the dips. The blue triangles denote the periods derived from the simulation without resistivity. Red dots and green diamonds represent the estimate from the pendulum model with constant and varying g, respectively. In general, the model well predicts the periods.*

The periods obtained from the parallel velocity variation are in good agreement with the predictions from the (extended) pendulum model of Eq. (2), as shown on Fig. 2. Here, the measured periods are obtained from an FFT of the time series. Despite the highly non-linear nature of the oscillations of plasma blobs that fall from the top of the flux rope, their periods are well constrained by the pendulum model. Note that the period durations are on the order of $5-10$ minutes, which is short compared to LALO periods of 60 minutes or more [1]. Third, the damping time of the oscillations varies throughout the prominence body. As can be seen on Fig. 1, many field lines show a relatively quick damping. Strikingly however, some field lines seem to witness a temporary increase in amplitude between $7800-9000$ s (*e.g.* the bottom four field lines, or the seventh field line counted from above). This effect was already reported by [5] and could be a result of some energy transfer between field lines, perhaps influenced by mass accreted from neighbouring field lines. We observe very weak to no damping of the oscillations on those field lines.

N.B. would like to express his gratitude to Valeriia Liakh for providing guidance in performing the analysis of these oscillations.

References

[1] I. Arregui, R. Oliver, J.L. Ballester, Living Reviews in Solar Physics, **15(1)** 1-154 (2018).

[2] N. Brughmans, J.M. Jenkins, R. Keppens, Astronomy & Astrophysics (under review).

[3] J.M. Jenkins, R. Keppens, Astronomy & Astrophysics **646**, A134 (2021).

[4] R. Keppens, J. Teunissen, C. Xia, O. Porth, Computers & Mathematics with Applications **81**, 316-333 (2021).

[5] V. Liakh, M. Luna, E. Khomenko, Astronomy & Astrophysics **637**, A75 (2020).

[6] M. Luna, J. Terradas, J. Karpen, J. Ballester, Astronomy & Astrophysics **660**, A54 (2022).