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Simulating the Dynamics of Coronal Plasma Condensations

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Abstract. We present numerical MHD simulations of the dynamics of cool plasma condensations in a coronal loop. We address 2 mechanisms for how coronal rain leads to the excitation of coronal loop oscillations. We find that the combined effect of pressure gradients in the coronal loop plasma and magnetic tension force resulting from changes in magnetic field geometry explains observed sub-ballistic motion of coronal rain and longitudinal oscillations of the individual condensations. We also find that the condensations can excite sustained, small amplitude, vertically polarised transverse loop oscillations.

Keywords. Magnetohydrodynamics (MHD), Sun: corona, Sun: oscillations, Sun: magnetic fields

1. Introduction

Otherwise hot and diffuse solar corona contains numerous cool and dense plasma structures in the form of prominences and coronal rain. Coronal rain consisting of down-falling cool plasma condensations is a phenomenon occurring in footpoint-heated coronal loops as a result of thermal instability. Recent high resolution observations have shown that coronal rain is much more common than previously thought, suggesting its important role in the chromosphere-corona mass cycle. Due to its origin, coronal rain also provides us with physical insight into the atmospheric thermal cycle and into prominence formation and evolution.

2. The model and numerical setup

We use Lare2d (Arber *et al.* 2001), a 2.5D shock-capturing Lagrangian remap code that solves MHD equations on a staggered Cartesian grid. Thermal conduction and radiative loss terms are not included in the energy equation. The density variation between the loop and the background medium is given by the symmetric Epstein profile. We assume a realistic temperature profile representative of an atmosphere consisting of a cool chromosphere, transition region layer and hot corona. The vertical density profile for the non-isothermal stratified atmosphere is determined by numerically solving for a hydrostatic pressure balance. For analysis of the condensation dynamics a long rectangular domain is used, corresponding to a straightened coronal loop (Figure 1). This configuration uses uniform vertical magnetic field and reduced gravity to account for the semicircular model of the loop. A condensation, represented by a Gaussian density enhancement with chromospheric temperature is introduced near the loop apex and let to evolve. For analysis of the excitation of vertical loop oscillations a square domain is used using a current free magnetic field configuration to model a coronal arcade (Figure 1). A cool and dense extended condensation region is located at the loop apex.

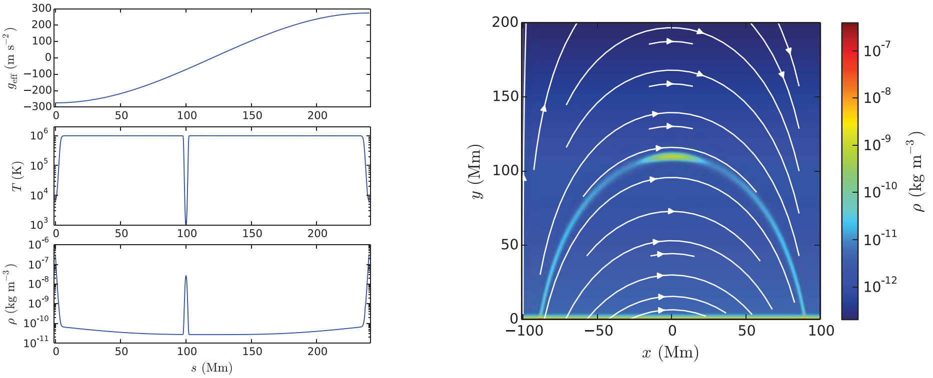

Figure 1. Left: Initial configuration of the straightened loop. Plots show the variation of effective gravity, temperature and density along the centre of the domain. Right: Initial density configuration of the coronal loop with cool condensation region. The white lines show the B-field direction.

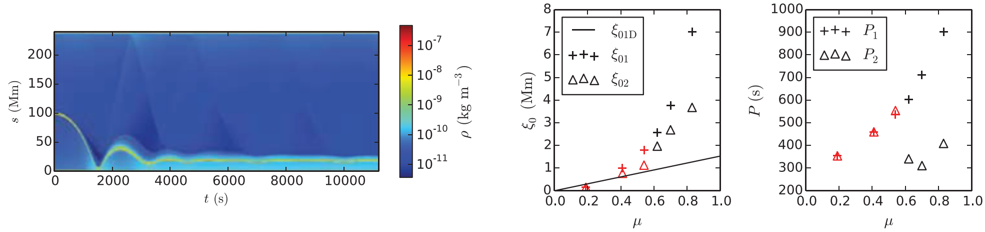

Figure 2. Left: Time distance plot of the density evolution along the centre of the loop. Right: Amplitudes and periods of the oscillations for different condensation region masses. Solid line shows amplitudes predicted by 1D model by Verwichte *et al.* (2017).

3. Results

3.1. *Condensation dynamics*

The downward motion of the condensation becomes increasingly sub-ballistic for low condensation region densities and large magnetic field values. If the density or magnetic field cross the threshold value, the condensation does not follow simple free fall motion but is instead found to oscillate, until it eventually settles in an equilibrium position (Figure 2). Analysis of the evolution of the individual forces acting on the condensation suggests that the oscillatory motion is caused by the combination of two forces: gas pressure force resulting from the compression of the underlying loop plasma confined below the blob and magnetic tension force resulting from bending of the magnetic field lines. The problem can therefore be approximated as an MHD piston aligned with the magnetic field. We consider the dynamics of the plasma blob as a perturbation of the equilibrium where pressure forces above and below the blob match the gravity on the blob. For small-amplitude perturbation a dispersion relation is derived that relates the field-aligned oscillation period of the rain blob with the blob-plasma density ratio, equilibrium position and density scale-height (Kohutova & Verwichte 2017a). Although in high resolution solar observations the majority of coronal rain condensations are seen to fall directly towards the solar surface, individual blobs are sometimes observed to longitudinally oscillate up and down before falling (Kohutova & Verwichte 2016, Verwichte *et al.* 2017). The mechanism investigated above is therefore likely responsible for this type of observed motion.

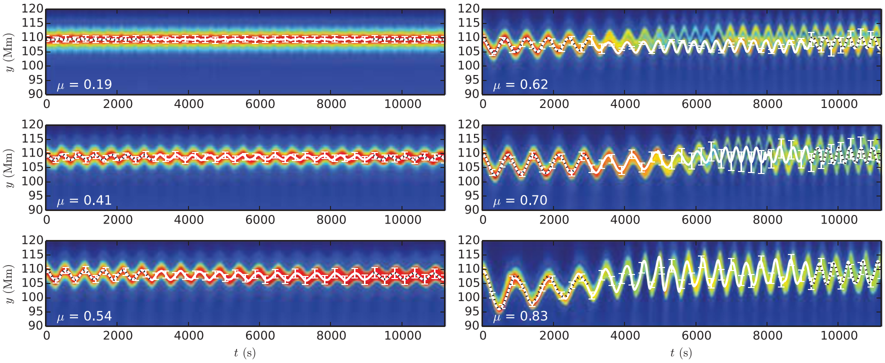

Figure 3. Time-distance plots of the loop apex position for different condensation region masses. Oscillation period decreases after condensations fall towards the surface.

3.2. *Vertical oscillations*

The presence of the dense condensation region displaces the axis of the loop downwards, which triggers vertical loop oscillations with the oscillation periods and amplitudes increasing with the overall condensation mass (Figure 2). The amplitudes predicted by 1D mechanical model by Verwichte *et al.* (2017) agree with simulation amplitudes for lowest masses of the condensation region, while at higher masses the two diverge and the mechanical model underestimates the amplitudes. This is as expected given that the assumptions made by the mechanical model (point-line condensation, constant loop length) only agree with the simulated scenario for low condensation region masses. As the condensations fall towards the solar surface under the influence of gravity, the distribution of the mass along the loop changes. This change in the loop density profile leads to a change in the period of the fundamental kink mode of the loop (Figure 3). The ratio of the initial to final oscillation period also increases with increasing condensation mass. The simulated period ratio can be compared with values deduced from 1D model for fundamental kink mode frequency of a long thin loop with longitudinally varying density:

$$\frac{\mathrm{d}^2\xi}{\mathrm{d}s^2} + \frac{\omega^2}{C_\mathrm{k}^2}\xi = 0$$

where ξ is the loop displacement and $C_\mathrm{k}(s)$ reflects the corresponding density profile, reaching good agreement for high condensation region masses (Kohutova & Verwichte 2017b). The first observational evidence of excitation of vertical coronal loop oscillations by coronal rain was shown in Verwichte & Kohutova (2017). The observations presented therein also showed a change of the oscillation period caused by the drainage of the coronal loop mass, in agreement with simulation results presented in this work.

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