Space Weather of the Heliosphere: Processes and Forecasts
Proceedings IAU Symposium No. 335, 2017
C. Foullon & O.E. Malandraki, eds.

doi:10.1017/S1743921317011024

Excitation and Evolution of Transverse Loop Oscillations by Coronal Rain

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Abstract. We present evidence of the excitation of vertically polarised transverse loop oscillations triggered by a catastrophic cooling of a coronal loop with two thirds of the loop mass comprising of cool rain mass. The nature and excitation of oscillations associated with coronal rain is not well understood. We consider observations of coronal rain using data from IRIS, SOT/Hinode and AIA/SDO in a bid to elucidate the excitation mechanism and evolution of wave characteristics. We apply an analytical model of wave-rain interaction, that predicts the inertial excitation amplitude of transverse loop oscillations as a function of the rain mass, to deduce the relative rain mass. It is consistent with the evolution of the oscillation period showing the loop losing a third of its mass due to falling coronal rain in a 10-15 minute time period.

Keywords. (magnetohydrodynamics:) MHD, Sun: atmosphere, Sun: oscillations

1. Introduction

Coronal rain are dense cool plasma blobs that form near the top of coronal loops and fall towards the solar surface guided by the magnetic field (e.g. Schrijver 2001, Antolin *et al.* 2010). They are caused by catastrophic cooling of coronal plasma in response to localised heating increasing the amount of radiating in a loop (e.g. Müller *et al.* 2005). Coronal rain frequently exhibits transverse oscillatory motions (Antolin & Verwichte 2011, Kohutova & Verwichte 2016). These oscillations typically have periods in the order of a few to tens of minutes with projected displacement amplitudes of hundreds of to a thousand km. The physical mechanism for excitation of such oscillation in quiescent coronal loops is unclear. Verwichte *et al.* (2017) demonstrated that the presence of coronal rain through its concentrated mass may excite transverse loop oscillations and thus provide an additional seismological tool to determine the fraction of the rain mass relative to the total loop mass. This mechanism could explain the excitation of some rain oscillations such as the short-period oscillations measured by Kohutova & Verwichte 2016).

The approximate expressions found by Verwichte *et al.* (2017) are based on an analytical model where rain blobs are point masses, which displace the loop by its gravity. For loop length, L, inclination angle of the loop plane with respect to the photospheric normal, θ and fraction of coronal rain mass relative to the total loop mass, m/M, the expected displacement amplitudes of the excited oscillation, for fundamental horizontally and vertically polarised modes, are given by

$$\xi_{0,\wedge} = (9.6 \pm 0.7)\, 10^{-3} \sqrt{\frac{2\theta}{\pi} \frac{m}{M}}\, L \ , \ \xi_{0,\perp} = (5.0 \pm 0.6)\, 10^{-3} \sqrt{1 - \frac{2\theta}{\pi} \frac{m}{M}}\, L \ . \qquad (1.1)$$

These expressions are in agreement with full MHD simulations in the limit of small rain masses but underestimate the amplitude for larger masses (Kohutova & Verwichte 2017a,

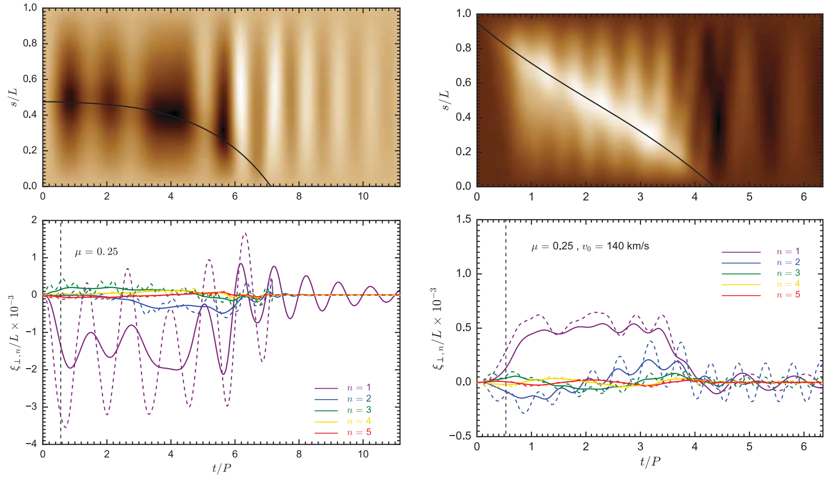

Figure 1. Left: Excitation of vertical oscillations due to a finite mass rain blob ($m/M = 0.2$) released near the loop top. The rain mass is exponentially ramped up over a typical time of 100s. Top: Displacement along the loop as a function of time with blob path superimposed. Bottom: Amplitudes of the five first wave mode harmonics as a function of time. Dashed lines are undamped modes (from Verwichte *et al.* 2017). Right: Same but for a rain blob launched into the loop from a foot point at a speed of 140 km/s. This case highlights the effect of wave excitation via the centrifugal force.

2017b). Excitation of vertical oscillations may also be achieved through the centrifugal force from fast-moving rain, with speeds in excess of $\sqrt{g_{\odot} R} \sim 100$ km/s, displacing the loop outwards (see Figure 1).

2. Observation

We present observations by IRIS in Si IV and Hinode/SOT in Ca II of a vertically polarised transverse oscillation in a coronal loop of length 80 Mm with coronal rain on the 27th August 2014. From 08:42 UT cold plasma condensations are forming at the loop top that quickly fill up to 60% of the loop length. At the same time a fundamental vertically polarised transverse oscillation becomes visible as periodic up and down motions of the condensations (see Figure 2). A tried and tested semi-automated method is used to determine the loop top position as a function of time at two time intervals, and we fit an undamped sinusoidal signal with a background trend (Verwichte *et al.* 2004, Verwichte *et al.* 2009). Critically, for the two time intervals we find different displacement amplitudes and periods, i.e. $\xi_{0,1} = 0.22 \pm 0.07$ Mm, $P_1 = 2.6 \pm 0.1$ min, and $\xi_{0,2} = 0.15 \pm 0.07$ Mm, $P_2 = 2.1 \pm 0.1$ min. From inserting these values into Eq. (1.1) the rain mass ratios at the two time intervals are deduced to be (Verwichte & Kohutova 2017): $(m/M)_1 = 0.58^{+0.4}_{-0.3}$, $(m/M)_2 = 0.38^{+0.4}_{-0.2}$. 58% of the loop mass is rain at the start of the event when condensations are seen forming along 60% fraction of the loop length. This result is similar to what had been found to explain the short-period horizontally polarised transverse oscillations by Kohutova & Verwichte (2016) and consistent with the finding of Antolin *et al.* (2015) that coronal rain may make up most of the loops mass. Towards the end of the visible oscillation, the mass fraction has dropped down to 40%. The evolution of period independently holds information on the rain mass. Assuming the hot loop mass does not change, we deduce from the period ratio that $(m/M)_2 = 1 - (P_1/P_2)^2 [1 - (m/M)_1]$ $= 0.34^{+0.7}_{-0.2}$, which independently confirms the earlier found value.

https://doi.org/10.1017/S1743921317011024 Published online by Cambridge University Press

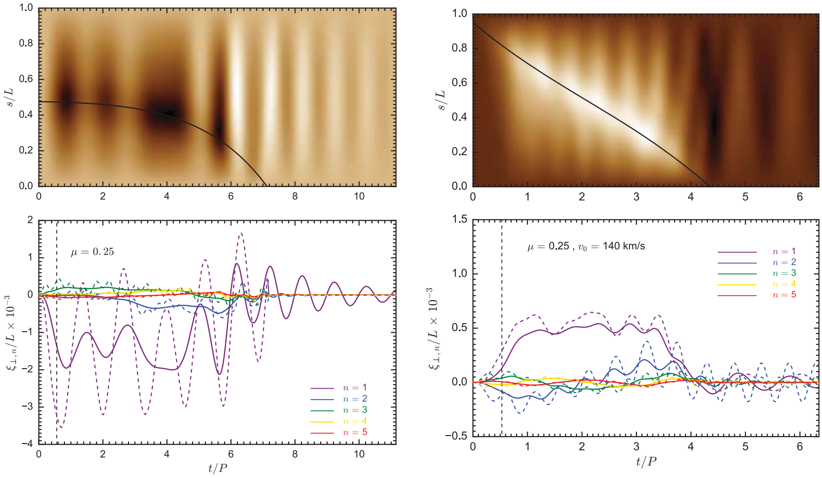

Figure 2. Top left: Partial FOV of the IRIS Si IV observations at three times. Bottom left: Time-distance cuts perpendicular (top) and parallel (bottom) to the loop axis in the two IRIS data sets. Right top: Loop position obtained from IRIS as a function of time. Right middle: Loop displacement as a function of time obtained by subtracting the linear profile from the loop position time series. The red and green curves are fitted sinusoidal curves with the corresponding parameters listed. Right bottom: Position of individual rain blobs as distance relative to the approximate loop top as a function of time (from Verwichte & Kohutova 2017).

Eq. (1.1) assumes an instantaneous appearance of the rain blob. In reality rain blobs form on a radiative cooling time-scale $\tau_{\rm rad} = (k_{\rm B}/(\gamma - 1)\,\chi)n_e^{-1}T^{1-\alpha}$, where we have assumed a piece-wise linear radiation profile as a function of temperature. For a typical coronal loop with temperature $T = 10^6$ K and mass density $\rho = 10^{-11}$ kg/m^{-3}, we obtain $\tau_{\rm rad} = 5$ mins. We have used SDO/AIA images and the DEM inversion method by Hannah & Kontar (2012) to estimate the temperature and density as a function of time during the condensation phase of the thermal limit cycle. We obtain $\tau_{\rm rad}$=500 s, i.e. the same order of magnitude but larger. We may model this gradual appearance by ramping up the rain mass on the same time-scale (see Figure 1). However, this does not take into account pressure effects at low masses. Full MHD simulations with self-consistent thermal instability are required to answer this question more definitively.

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https://doi.org/10.1017/S1743921317011024 Published online by Cambridge University Press