Inducing prominence oscillations with a shock wave

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Abstract We explore different ways of introducing a realistic source of prominence oscillations. Using 1D simulations, we mimick a solar disturbance by introducing energy into the system over a certain time and spatial scale. Based on the energy source parameters, the velocity profile of the resulting shock wave changes. By changing in particular, the time scale and the height of the source region we showed that this significantly influences formation and evolution of the resulting shock wave.

Prominence oscillations and their sources

Prominences are large scale structures in the solar corona, about two orders of magnitude colder and denser than the surrounding coronal plasma. There is a lot we don't know about prominences and also about the corona they inhabit, which is why studying them and the way they behave is crucial. One of the more striking characteristics of prominences is that they oscillate and quite often, eventually erupt. The oscillations are usually divided in large amplitude oscillations (LAOs) and small amplitude oscillations (SAOs). Those with a velocity amplitude larger than 20 km/s are considered as LAOs and those with a smaller velocity amplitude, are considered as SAOs [1, 2]. There exist different sources of prominence oscillations, from small scale triggers located in the vicinity of a prominence to large scale events. Small scale triggers can be microflares or subflares located in the vicinity of a footpoint of a coronal loop in which the prominence resides or may result from photospheric motions. Large scale events are usually extreme-ultraviolet (EUV) waves created by an erupting coronal mass ejection (CME) or a flare located somewhere in the prominence surroundings.

The goal of this work is to properly parametrize a shock wave responsible for triggering prominence oscillations. We present 1D simulations with which we explored how to include a source area in our domain with a simple prominence positioned at the center of it.

Methods

The fact that the corona is strongly magnetized ($\beta < 1$) allows us to use simple 1D magnetic field line guided dynamics. We perform the simulation in a gravitationally and thermally stratified coronal arcade system with a transition region at the height of 2.72 Mm (Fig. 1). The magnetic arcade shown on Fig. 1 has a prominence artificially created by increasing the density while keeping the pressure constant. We solve the following 1D, hydrodynamic (HD) equations:

$$\frac{\partial\rho}{\partial t}+\frac{\partial(\rho v)}{\partial x}=0 \tag{1}$$

$$\frac{\partial(\rho v)}{\partial t}+\frac{\partial(\rho v^2+p)}{\partial x}=\rho g(x) \tag{2}$$

$$\frac{\partial e}{\partial t}+\frac{\partial(ev+pv)}{\partial x}=\rho g(x)v+S \tag{3}$$

where ρ and v are plasma density and velocity, p is the gas pressure. $g(x)$ is gravity along an isolated magnetic field line (Fig. 1). e is the energy density and S represents source terms in the energy equation. We use an open source simulation code, the MPI - Adaptive Mesh Refinement - Versatile Advection Code [3]. Fixed boundary conditions are implemented to represent the line-tied conditions at the footpoints of the coronal loop.

We create the shock wave by increasing the energy over a circular area in our domain.

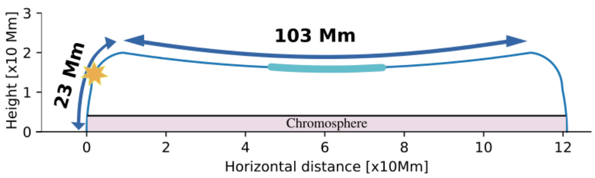

Figure 1: Geometry of the magnetic arcade with the star marking the position of the source.

Numerically, we introduce an additional source described with the following equation:

$$S(x,t)=S_0\cdot exp\left[-\frac{r^2}{R^2}-\frac{(t-t_{peak})^2}{t_{scale}^2}\right] \tag{4}$$

where $r=[(x-x_s)^2]^{1/2}$ is the radial distance around the source center, x_s (equivalent to the height of the source region) and R is the radius of the area over which we introduce the source. t_{peak} is when the source maximizes, t_{scale} determines its duration. S_0 determines the amplitude of our source, calculated as the energy of the source per unit volume and time (erg cm^{-3} s^{-1}).

Time discretization is done with a fivestep (strong stability preserving) fourth-order Runge-Kutta method, while for the spatial discretization we employ a Harten-Lax-van Leer (HLL) approximate Riemann solver combined with a standard shock-capturing slope limiter. To ensure stability the courant number used in these simulations is 0.8. Furthermore, to attain high resolution our mesh is uniform with 2800 cells, which allows us to resolve lengths of 53.6 km on a loop system of total length of 150 Mm.

Results and Conclusion

In order to introduce the source of an EUV wave we tried two different numerical approaches. The first approach was introducing the source region directly, as part of the initial conditions.

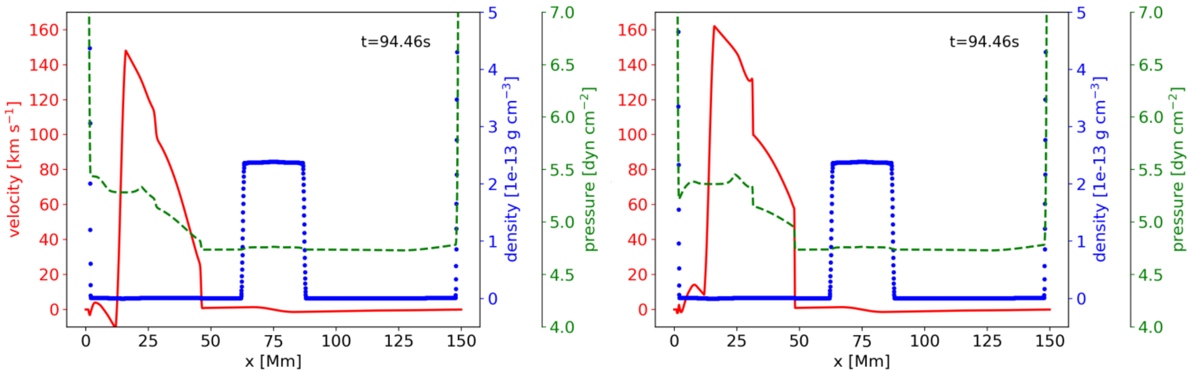

Figure 2: Velocity profile (full red line), density profile (dotted blue line), and a pressure profile (dashed green line) at t=94.46s, resulting from two source regions differing only in the t_{scale} parameter, 60 and 85 s on the left and right panel, respectively (x_s=14 Mm, R=2 Mm, S_0=20 dimensionless).

Even though this results in a shock wave, it is not preferable, since the energy increase is instantaneous which is numerically challenging at very high energies (strong shock waves). The second approach introduces the source over a certain time and spatial scale, as implied by eq. 4. We take t=0 as 85 s before the source reaches it's maximum. We keep R fixed to 2 Mm. If the time scale is too large and/or the amplitude S_0 too small, the energy we impose on the system will not turn into the dynamic energy of a propagating shock wave, but to a local entropy change, where density and temperature adjust while the pressure stays constant. In the first case, we keep S_0 and other parameters, t_{peak}, R, x_s constant and change only the time scale over which we introduce the additional energy into the system. By changing the time scale and keeping S_0 constant we are actually changing the amount of energy we include into the system (Tab. 1).

t_{scale} [s]	E [$\times 10^{26}$ erg]	x_s [Mm]	E [$\times 10^{26}$ erg]
8.5	1.11	4	1.58
25.5	3.32	8	3.16
42.5	5.53	12	4.74
69.5	7.74	14	5.53
85	11.1	16	6.32

Table 1: Time scale (t_{scale}) and height (x_s) of the source region with their corresponding energies, with keeping the R, t_{peak} and x_s (t_{scale}) constant.

In Fig. 2 we can see two velocity profiles (full red line) at the same moments, but resulting from two source regions differing only in the t_{scale} parameter (the density profile, blue dotted line helps in visualizing the position of the prominence). We can clearly see how the profiles differ just by introducing more energy into the system. In order to quantify this, we did a simple

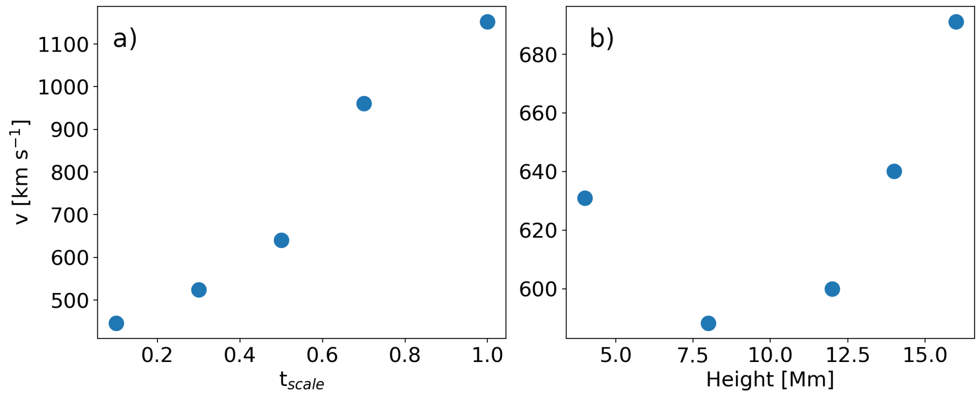

Figure 3: Panel a) shows how the velocity (of the disturbance from the source region) changes with changing the time scale over which we introduce the energy of the source. Panel b) shows the same but as a response to changing the height (x_s parameter) of the source region.

analysis of the time it takes for the disturbance from the source region to reach the left edge of the prominence at 63 Mm, i.e the velocity by which the influence of the source propagates. On Fig. 3 we can see how the mentioned velocity changes in relation to changing the time scale, t_{scale} and the height, x_s. Increasing the time scale we directly increase the energy input in the system over a fixed area. As a result, the velocity by which the disturbance propagates steadily increases (left panel of Fig. 3). From the right panel of Fig. 3 we see that same velocity show a different behavior by changing the height of the source region (and with it again the energy, Tab. 1). Increasing the height from 4 to 8 Mm, the velocity decreases, even though the total energy we introduce into the system actually increased. Changing the height of the source region does not induce a straight forward change in the velocity as does changing the time scale. Even though we increase the energy input into the system, at lower heights the disturbance has more difficulty propagating due to the higher local density and hence, higher inertia to overcome. As a result, the velocity decreases until approximately 8 Mm. Starting from 12 Mm, it seems the disturbance can again propagate more freely and has a clear increase in velocity with increasing the energy. This kind of parametric study, paves the way to future multidimensional MHD simulations, where we want to induce (and then study) prominence oscillations caused by a realistic shock wave. This could even allow us to relate source properties with particular type of prominence oscillations.

References

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