Flows in coronal loops driven by Alfvén waves: 1.5 MHD simulations with transparent boundary conditions

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Abstract. We investigate time-dependent siphon flows in coronal loops driven by Alfvén waves. We consider a 1.5 D isothermal, MHD model in which the coordinate is the abscissa along the loop, with an external gravity field reversing sign in the middle, and a uniform magnetic field parallel to the x-axis. We use transparent boundary conditions, meant to describe the upper part of the loop. The reaction of the loop to Alfvén waves depends entirely on whether we allow or not incoming parallel velocity fluctuations: only in the latter case do transonic flows arise, but the flow is in that case generated by a nonlinear coupling of the waves with the boundaries.

INTRODUCTION

We consider in this paper the interaction between Alfvén waves and the plasma flow along a closed coronal loop. The response of closed magnetic structures to Alfvén waves has been much studied in the MHD framework, in the context of coronal heating, but the generation of parallel flows by wave pressure has been studied in open field regions only. We consider a loop model with weak stratification, and transparent boundary conditions. In doing so, we basically model the coronal part of the loop, and exclude wave trapping, reflection and resonance. Our motivation is that, if Alfvén waves are to contribute to acceleration of the plasma in open regions to generate the fast solar wind, they should also be present in closed regions. An indication that Alfvén waves could have significant effects also in closed loops is given by recent observations [1], and by a numerical study of a global solar wind model [2] where Alfvén waves induce supersonic flows along closed loops in the equatorial region. In order to understand the conditions for the onset of such flows, we consider here the more restricted problem of a single closed loop, modeled as a one-dimensional domain with uniform magnetic field, and a stratification maintained by an artificial gravity changing sign in the middle of the loop.

The problem of interest is a time-dependent version of siphon flows, while in previous studies, only stationary flows were investigated, with fixed pressure boundary conditions [3,4]. Siphon flows show properties combining those of stellar winds for the upward flow and of accretion flows for the downflow. We investigate here whether Alfvén waves can trigger the transition from a static stratification to a supersonic flow. It is indeed possible that large pressure deviations result from small wave pressure imbalance, in particular when the plasma β is low enough, as the Alfvén wave becomes unstable [5]. For simplicity, we consider circularly polarized waves. As we will see, the result depends closely on boundary conditions.

MODEL AND BOUNDARY CONDITIONS

The initial hydrostatic equilibrium stratification has a density equal to 2.7 at the boundaries, and 0.4 in the rarefied middle of the loop. It is determined by an artificial gravity $g_x = -T_0/H_0 \sin(x)$ where T_0 is the temperature in convenient units $T=P/\rho= c^2$, where c is the sound speed), and H_0 is the scale height. The latter is about equal to the height of the loop: H_0=1. The plasma is isothermal (γ=1), so that the temperature is uniform and constant. As a result, the initial density profile is $\rho = \exp(\cos x)$. The length of the loop is 2π. The parallel component B_x of the magnetic field is constant, since divB=0; it is fixed to be unity, so the initial magnetic field is $B_0 = (1,0,0)$. The initial Alfvén speed thus varies between 0.6 (at boundaries) and 1.65 (middle of the interval), so that the traversal time of an Alfvén wave is about 2π. The temperature is $T_0 = 0.1$ corresponding to a sound speed c=0.33, and an initial plasma βsuch that $0.073 < \beta < 0.54$, but we will mention runs with lower β, $0.007 < \beta < 0.054$ (T_0 = 0.01).

The injected wave is circularly polarized, with angular frequency ω=5 (which lead to about 5 wavelengths inside the domain). The wave amplitude is progressively increased in a quarter of a wave period, using a ramp function $A(t) = 1-\exp(-(t/\tau)^4)$, with $\tau=\pi/(2\omega)$. The amplitude of the wave is $\varepsilon = B_{perp}/B_x = 0.05$. The wave components injected are:

$$B°_y = A(t)\varepsilon\cos(\omega t);\ B°_z = A(t)\varepsilon \sin(\omega t) \qquad (1)$$

The wave is injected both at x=0 and 2π, with a non zero delay δT at $x=2\pi$. This delay produces a small magnetic pressure difference between both boundaries. Let us show it in the non-stratified case. The addition of two waves propagating in opposite directions produces a magnetic pressure profile which is:

$$B_{perp}^2 = 2\varepsilon^2+2\varepsilon^2\cos(2kx+\phi) \qquad (2)$$

where k is the wavenumber and ϕ is the phase difference between the two waves. The resulting pressure difference between the two boundaries is

$$\delta B_{perp}^2 = 2\varepsilon^2(\cos(\phi)-\cos(4\pi k+\phi)) \qquad (3)$$

Whenever 2k is not an integer, there is a (small) wave pressure difference between the two boundaries that scales as ε^2. If the frequencies of the two waves differ, the total magnetic pressure fluctuates with time, but this time dependence remains small if the frequencies are close to one another.

We use a finite difference compact spatial scheme, and a third order Runge-Kutta temporal scheme with a kinematic viscosity and a magnetic diffusivity, as well as a (small) artificial diffusion for the density.

There are six degrees of freedom in isothermal MHD. For subsonic and subalfvénic flows, we must specify the three incoming characteristics: Alfvén, slow and fast, denoted here as $L_{a,s,f}^+$ at x=0 and $L_{a,s,f}^-$ at $x=2\pi$ [2,5]. It sounds reasonable to inject Alfvén waves via the Alfvén characteristics L_a, as in global solar wind simulations [6,2], but in the present 1.5D case we found that this leads to a systematic drift of the magnetic pressure. To prevent the pressure drift, we control separately the injected magnetic field components, as done in [5]. (Note that the magnetic pressure of the injected wave is constant but the total magnetic pressure may vary with time, although with no systematic drift). Consider, to be specific, the x=0 boundary. The equations for the injected magnetic field components read, in term of the three rightward propagating characteristics:

$$(1/\sqrt{\rho})\partial b_y^+/\partial t=-\beta_z L_a^+-\beta_y/\rho\{\alpha_f L_s^+ + \alpha_s L_f^+\} \qquad (4)$$

$$(1/\sqrt{\rho})\partial b_z^+/\partial t=-\beta_y L_a^+-\beta_z/\rho\{\alpha_f L_s^+ + \alpha_s L_f^+\} \qquad (5)$$

where $\alpha_{f,s}$ are defined in terms of the Alfvén, fast and slow velocities [5]. In order to prescribe $\partial b_y^+/\partial t = dB°_y/dt$ and $\partial b_z^+/\partial t = dB°_z/dt$, where B°(t) is the function given in (1), we have to satisfy to (using $\beta_y^2 + \beta_z^2 = 1$):

$$L_a^+ = - \beta_y (1/\sqrt{\rho})dB°_z{}^+/dt + \beta_z (1/\sqrt{\rho})\, dB°_y/dt \qquad (6)$$

$$\alpha_f L_s^+ + \alpha_s L_f^+ = - \beta_y \sqrt{\rho}\, dB°_z{}^+/dt - \beta_z \sqrt{\rho}\, dB°_y/dt \qquad (7)$$

A natural choice for the third condition is to set to zero the slow mode injection,

$$L_s^+ = 0 \qquad (8)$$

The set (6-8), to be denoted C0, appears appropriate because in the linear limit it reduces to injecting the two polarizations of the Alfvén modes and no acoustic wave.

RESULTS

Fig.1 shows the plasma response to waves injected at both boundaries with a slight phase difference, in the moderate β case. The parallel (leftward) flow is seen to reach quasi-periodically a transonic regime. Correspondingly, there are large, low-frequency pressure fluctuations with amplitude more than an order of magnitude larger than the magnetic pressure difference between the two boundaries (Fig.2).

Fig.3 shows how the instability begins: the pressure first becomes larger at left boundary. It is finally not clear whether the long-term oscillation is due to the particular choice of boundary conditions, or if it is due to the variation of the conditions inside the loop induced by the wave.

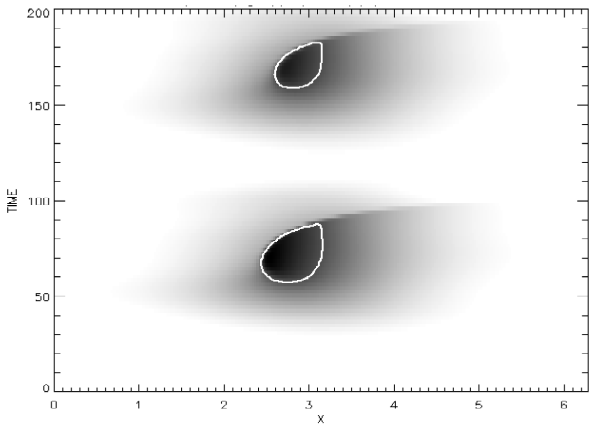

FIGURE 1. Parallel velocity of the plasma in space-time, in response to Alfvén wave injection, with boundary conditions C0: moderate β case. White lines: Mach=-1 isolines.

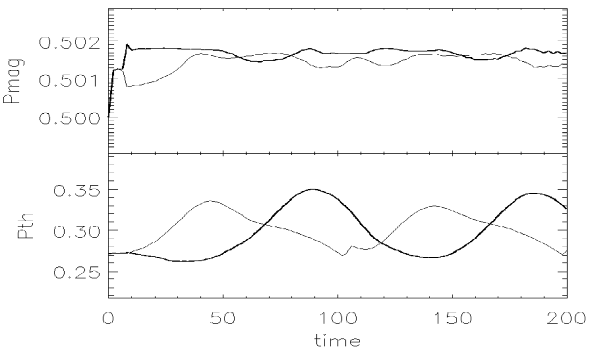

FIGURE 2. Pressure variations versus time at the boundaries (bold, x=0; plain, x=2π). Top: magnetic pressure; bottom: thermal pressure. Same run as Fig.1.

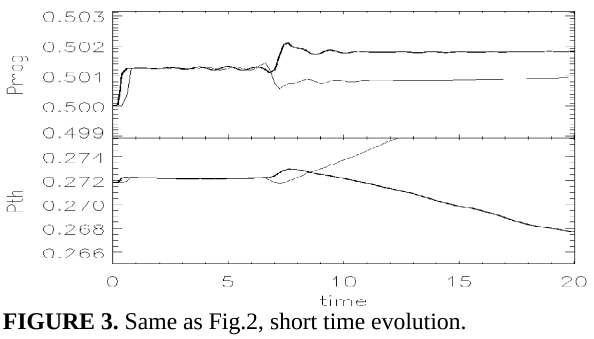

FIGURE 3. Same as Fig.2, short time evolution.

DISCUSSION

We have seen that the thermal pressure variation largely amplifies the magnetic pressure variation associated with the waves. To examine this process, we consider the simpler non-stratified case, and focus on the time period when the two wave trains reach the opposite boundaries.

Fig.4 shows the magnetic pressure, thermal pressure and parallel velocity at successive times. One sees that the magnetic pressure adopts the profile (2), but that the fluid pressure shows un abrupt variation at the boundaries when the waves reach the boundaries: the thermal pressure rises at x=0, and decreases at x=2π. Accordingly, there is a strong acceleration rightward at both boundaries. This corresponds to a (spurious) injection of u_x fluctuations, resulting from a nonlinear reflection of the Alfvén wave on the boundary, associated with a change in wave mode..

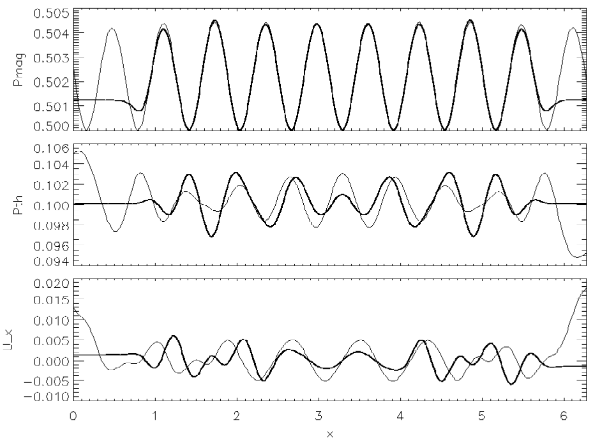

FIGURE 4. Profiles of the wave pressure (top), thermal pressure (mid panel) and parallel velocity (bottom), as the two waves reach the opposite boundaries, conditions C0. Times 6 (bold), and 8.

When one examines the equation for the parallel (incoming) velocity in terms of the incoming characteristics, one sees indeed that, except in the linear limit, the condition of no slow wave injection isn't enough to prevent the excitation of some parallel velocities, whenever there is some fast mode injection:

$$\partial u_x^+/\partial t = (1/c)(v_s\alpha_s L_s^+ - v_f\alpha_f L_f^+) \tag{9}$$

(c is the sound speed and $v_{f,s}$ are the fast and slow speeds).

To examine whether we can suppress this coupling with the boundary, we consider the even simpler model of an isothermal non conducting gas, to which we apply from the start an external force corresponding exactly to the gradient of the magnetic pressure of the previous situation, frozen to the state shown in Fig.3 at time t=8 when the waves have travelled the whole domain. We find in that case no spurious acceleration at the boundary, and the velocity fluctuations generated within the medium by the external force propagate away at the sound speed. There remains only a stationary pattern of thermal pressure fluctuations necessary to balance the external force mimicking the wave pressure, with a very slow systematic flow.

It is important to remark that, in this hydrodynamic version of the problem, there is only the acoustic characteristic to impose, namely $L_s^+ = 0$, which is here completely equivalent to $\partial u_x^+/\partial t = 0$. In the MHD case, we have seen that in the nonlinear case at least, no slow wave injection is not equivalent to no injection of parallel velocity. When looking at (9), we find that $L_s^+ = 0$ is equivalent to $\partial u_x^+/\partial t = 0$ only in either in the linear limit, or when dealing with a simple wave, that is, not in presence of two waves propagating in opposite directions.

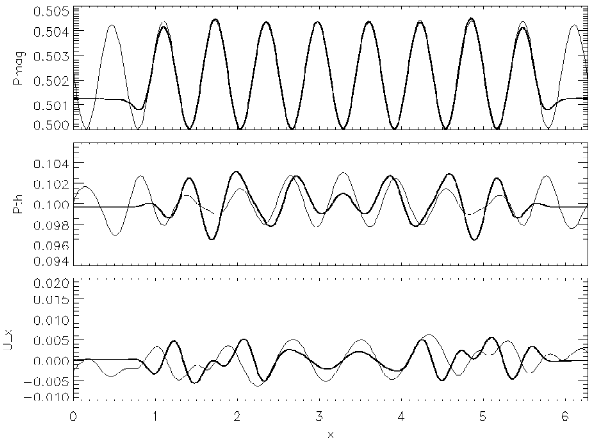

FIGURE 5. Same caption as Fig.4, boundary conditions C2.

We now come back to the MHD problem and replace the condition $L_s^+ = 0$ by $\partial u_x^+/\partial t = 0$, or:

$$v_s\alpha_s L_s^+ - v_f\alpha_f L_f^+ = 0 \qquad (10)$$

We call C2 the set (6-7) and (10). When applying it first to the unstratified case, as shown in Fig.5, we see that the boundaries no longer suffer spurious acceleration, and that the pressure fluctuations remain at a small level, actually comparable to that obtained in the hydrodynamic case. Last, we apply conditions C2 to the stratified MHD case; we again find no large pressure imbalance (Fig.6), and, as a consequence, after transient fluctuations have escaped the loop, only a weak subsonic flow remains.

This remains true when we decrease the plasma β: although the wave decays into density fluctuations, the resulting flow does not reach a large Mach number. In conclusion, the reaction of the loop to Alfvén waves depends entirely on wether we allow or not incoming parallel velocity fluctuations: only in the latter case do transonic flows arise. On the other hand, we checked that purely reflecting conditions also do not lead to supersonic flows. True boundary conditions are more complex than just transparent or reflecting: in fact, the transparency of the chromospheric transition is frequency-dependent [7], and simulations including it are needed to decide whether Alfvén waves can trigger supersonic flows or not.

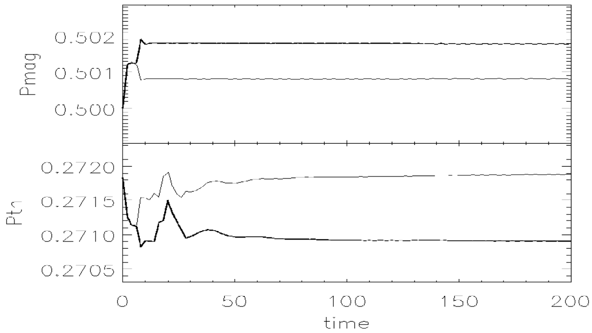

FIGURE 6. Pressure variations at the boundaries (bold, x=0; plain, x=2π). Top: magnetic pressure; bottom: thermal pressure (compare Fig. 2). Boundary conditions C2.

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