Formation of Coronal Shocks

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Introduction

Coronal MHD shock wave signatures (type II burst and Moreton wave) appear in close association with the flare impulsive phase and/or the coronal mass ejection (CME) acceleration phase. Flares and CMEs are very powerful dynamic processes, capable of generating plasma motions perpendicular to the magnetic field lines, which is a necessary requirement for the formation of magnetosonic shocks that excite type II bursts. The expansion creates a large-amplitude perturbation in the ambient plasma, which evolves into the shock after a certain time and distance owing to the nonlinear evolution of the wavefront profile [1], [2].

We consider an expanding two- and three-dimensional piston as a driver of an MHD shock wave (in a cylindrical and spherical symmetry, respectively). For the matter of simplicity we examine a constant-acceleration of the piston in an environment dependent on radial distance. In particular, *const.*, $1/r$ and $1/r^2$ phase velocities of a low-amplitude waves are analyzed and compared in high b (≈ sound) and low b cases. Our main interest is to find shock-formation time and distance under the mentioned conditions.

Model

The source-surface speed of the piston increases in time as $v(t) = at$ during the acceleration time t_{max} and gains the maximal velocity v_{max}. The initial piston-radius r_0 increases from the initial value r_{p0} at $t = 0$ as $r_p = at^2/2 + r_{p0}$ (Figure 2). Due to energy conservation, the signal amplitude has to decrease with increasing distance, which is basically different from the 1D model [2]. For example, in the case of $b >> 1$, where only the kinetic energy has to be taken into account, we use:

$$\underbrace{r u^2 w r_w^a}_{\text{energy flux}} = const. \Rightarrow g(u) r_w^a = const. \qquad (1)$$

($a = 1$ for cylindrical; $a = 2$ for spherical coord. system)

Generally, $g(u)$ depends on the characteristics of the ambient plasma, primarily on the value of b.

The basic characteristic of the non-linear wavefront evolution is that the wave speed, w, depends on the wave amplitude, u:

$$w(r) = w_0(r) + k\,u(r), \qquad (2)$$

where u is the flow speed. The parameter k and speed of low-amplitude perturbation $w_0(r)$ depend on b and radial distance; in the $b << 1$ case: $k = 3/2$, $w(r) = v_A(r)$ (Alfvén speed) [1] and $b >> 1$: $k = 4/3$, $w(r) = c_s(r)$ (sound speed) [2].

Equations (1) and (2) give differential equations for the flow speed $r_w(t)$. In the cylindrical and spherical coordinate system the equations governing the wave propagation can be expressed as:

$$\dot{r}_w + \frac{1}{a} r_e g_e^{1/a} g^{-(1+1/a)} \left\{ \frac{dg}{d\dot{r}_w} \ddot{r}_w + \frac{dg}{dr_w} \dot{r}_w \right\} = 0, \qquad (3)$$

where r_e, u_e, v_e, g_e are the signal position, flow velocity, the velocity of the piston, and g-function defined by Eq. (1) at the moment t_e when a given wave segment was created, respectively. It can be noticed that g-function is dependent only on r_w and dr_w/dt.

We present results only for three different radial dependencies of the magnetosonic speed of undisturbed ambient medium i.e. when $b >> 1$, namely: $w_{00}(r) = 500$ kms^{-1}, $w_{01}(r) = 500\ (r_{p0}/r)$ kms^{-1}, $w_{02}(r) = 500\ (r_{p0}/r)^2$ kms^{-1}. For $b << 1$ the difference in the final outcome is negligible, so only the high-beta shock formation time and distance are shown in the Figure 1.

Results

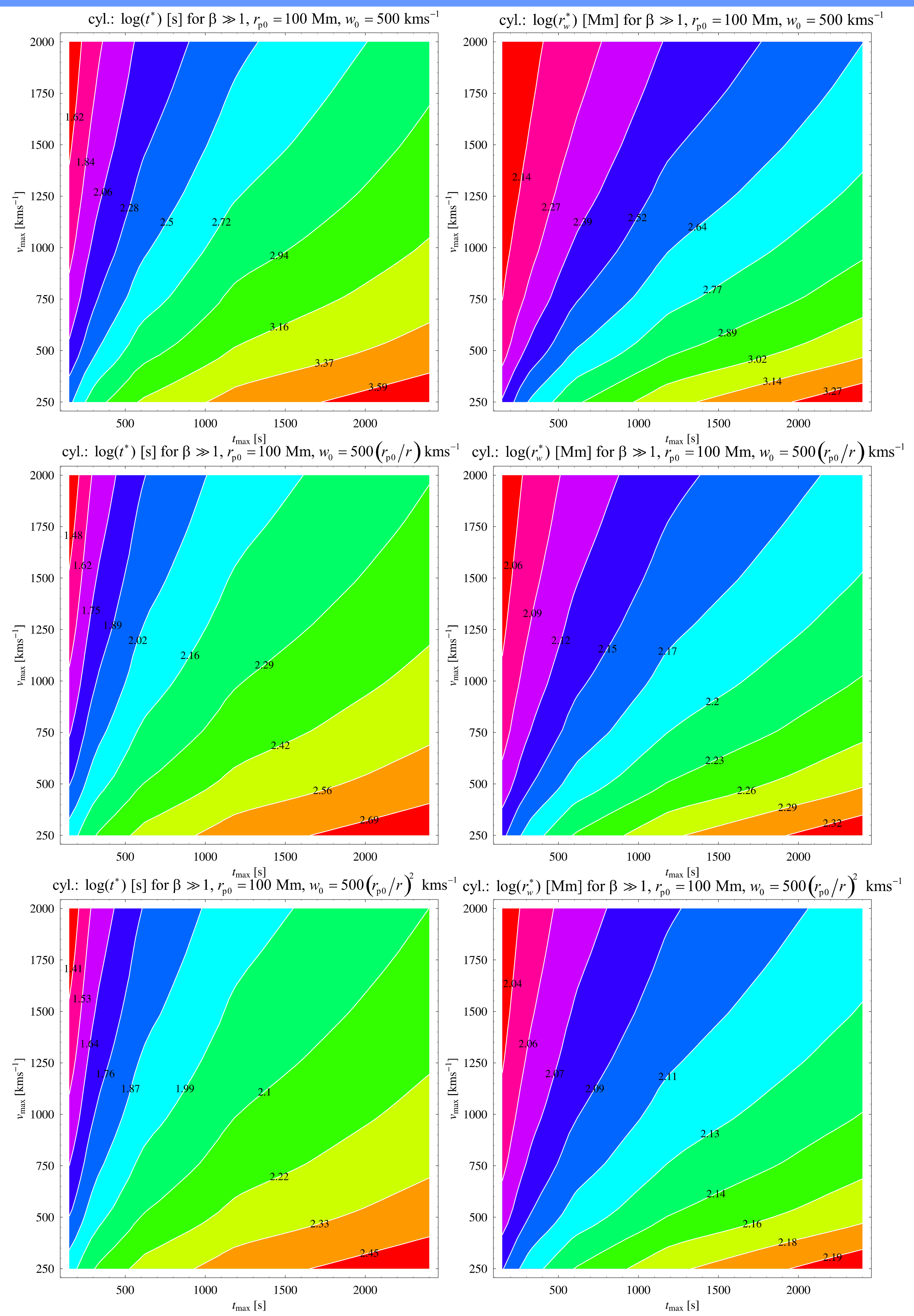

Figure 1. Logaritmically-scaled contour plots showing the dependence of the shock-formation time t^* (left) and distance r_w^* (right) on the acceleration time t_{max} and the final speed of the piston v_{max}, for the cylindrical $\beta >> 1$ case. The initial size of the source-surface, r_{p0}, equals 100 Mm. Three different radial dependencies of magnetosonic speed in undisturbed ambient medium, $w_0(r)$, are combined, namely: $w_{00}(r) = 500$ kms^{-1}, $w_{01}(r) = 500\ (r_{p0}/r)$ kms^{-1}, $w_{02}(r) = 500\ (r_{p0}/r)^2$ kms^{-1} from the top to bottom respectively. The contours are logarithmically spaced; the numbers at isolines represent log t^* (t^* in seconds) or log r_w^* (r_w^* in Mm). The graphs show dependences only in the cylindrical symmetry because the spherical case gives (qualitatively) similar results.

Summary of Results

We investigated how the shock-formation time and distance depend on the acceleration phase duration t_{max}, the maximum expansion velocity v_{max} (defining also acceleration a), the initial size of the piston, r_{p0}, in different ambient environment which is radially dependent. The results show that the shock-formation time t^* and the shock-formation distance r_w^* are:

§ approximately proportional to the acceleration phase duration t_{max},

§ shorter for a higher source speed v_{max},

§ only weakly dependent on the initial source size r_{p0},

§ shorter for a higher source acceleration a, and

§ lower in an environment characterized by steeper decrease of w_0

References

[1] Landau, L.D. and Lifshitz, E.M.: *Fluid Mechanics*, (Pergamon Press, 1987)

[2] Vršnak, B. and Lulić, S.: *Formation of Coronal MHD Shock Waves: I. The Basic Mechanism*, Solar Phys., **196** (2000) 157-180(24)

[3] Žic, T.; Vršnak, B.; Temmer, M.; Jacobs C.: *Cylindrical and Spherical Pistons as Drivers of MHD Shocks*, Solar Phys., (2008) in press

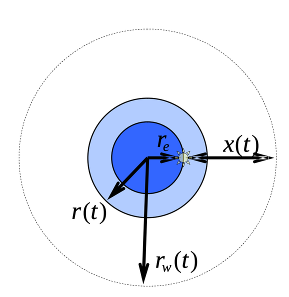

Figure 2. 3D (2D) piston signal propagation