Numerical Simulation of Coronal Waves Interacting with Coronal Holes. III. Dependence on Initial Amplitude of the Incoming Wave

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Abstract

We performed 2.5D magnetohydrodynamic (MHD) simulations showing the propagation of fast-mode MHD waves of different initial amplitudes and their interaction with a coronal hole (CH), using our newly developed numerical code. We find that this interaction results in, first, the formation of reflected, traversing, and transmitted waves (collectively, secondary waves) and, second, in the appearance of stationary features at the CH boundary. Moreover, we observe a density depletion that is moving in the opposite direction of the incoming wave. We find a correlation between the initial amplitude of the incoming wave and the amplitudes of the secondary waves as well as the peak values of the stationary features. Additionally, we compare the phase speed of the secondary waves and the lifetime of the stationary features to observations. Both effects obtained in the simulation, the evolution of secondary waves, as well as the formation of stationary fronts at the CH boundary, strongly support the theory that coronal waves are fast-mode MHD waves.

Key words: magnetohydrodynamics (MHD) – Sun: corona – Sun: evolution – waves

1. Introduction

Coronal waves were directly observed for the first time by the Extreme-ultraviolet Imaging Telescope (EIT; Delaboudinière et al. 1995) on board the Solar and Heliospheric Observatory (Domingo et al. 1995). They are defined as large-scale propagating disturbances in the corona and can be observed over the entire solar surface. The drivers of coronal waves are either coronal mass ejections or solar flares (for a comprehensive review see, e.g., Vršnak & Cliver 2008). In addition to numerous observations of the propagation of coronal waves, several authors described their interaction with coronal holes (CHs; Long et al. 2008; Veronig et al. 2008, 2011; Gopalswamy et al. 2009; Olmedo et al. 2012; Kienreich et al. 2013). The resulting effects of these interactions led to different interpretations of the nature of coronal waves.

Within the last 20 years, two main branches of theories have evolved that try to explain the nature of coronal waves either by using a wave approach or a so-called pseudo-wave approach. Wave theories consider coronal waves as fast-mode MHD waves (Thompson et al. 1998; Vršnak & Lulić 2000; Wang 2000; Wu et al. 2001; Ofman & Thompson 2002; Warmuth et al. 2004; Patsourakos et al. 2009; Patsourakos & Vourlidas 2009; Schmidt & Ofman 2010; Veronig et al. 2010; Lulić et al. 2013), whereas pseudo-wave theories interpret the observed disturbances as the result of the reconfiguration of the coronal magnetic field, caused by either Joule heating (Delanné & Aulanier 1999; Delanné et al. 2007), continuous small-scale reconnection (Attrill et al. 2007a, 2007b; van Driel-Gesztelyi et al. 2008), or stretching of magnetic field lines (Chen et al. 2002). Alternatively, coronal waves can be explained by hybrid models, that attempt to explain the disturbances by combining wave- and pseudo-wave models (Chen et al. 2002, 2005; Zhukov & Auchère 2004; Cohen et al. 2009; Liu et al. 2010; Chen & Wu 2011; Downs et al. 2011; Cheng et al. 2012).

Overall, there is a large amount of evidence suggesting that the wave interpretation can be considered as the best supported theory to explain the nature of coronal waves (Patsourakos et al. 2009; Warmuth 2015; Long et al. 2017). The main observational evidence for the wave theory is provided by authors who report waves being reflected and refracted at a CH (Long et al. 2008; Veronig et al. 2008; Gopalswamy et al. 2009; Kienreich et al. 2013) or show waves being transmitted through a CH (Olmedo et al. 2012) or demonstrate that EIT wave fronts are pushing plasma downwards (Harra et al. 2011; Veronig et al. 2011), which is also in agreement with the theory that EIT waves are fast-mode MHD waves.

The existence of stationary brightenings was one of the main reasons for the development of pseudo-wave theories. However, recent observations imply that fast EUV waves are capable of forming stationary fronts at the boundary of a magnetic separatrix layer (Chandra et al. 2016). Moreover, simulations of the propagation of coronal waves show that stationary fronts at a CH boundary can be caused by the interaction with obstacles like a magnetic quasi-separatrix layer (Chen et al. 2016) or a CH (Pantschitsch et al. 2017).

Pantschitsch et al. (2017) performed 2.5D simulations that showed that the interaction of a fast-mode MHD wave with a CH produces secondary waves (i.e., reflected, traversing, and transmitted waves) as well as stationary features at the CH boundary. The analysis of the secondary wave’s phase speeds in the simulations shows good agreement with observations, where the authors report waves being reflected and refracted at a CH (Kienreich et al. 2013) or being transmitted through a CH (Olmedo et al. 2012). The simulations by Pantschitsch et al. (2017) were performed by assuming a fixed initial density amplitude and a fixed CH density. In Pantschitsch et al. (2018), we focused on the comparison of different CH densities and on how they influence the morphology and kinematics of the secondary waves and stationary features. We found, e.g., that a small CH density leads to small amplitudes for the transmitted wave, the traversing wave, and the first stationary feature. Furthermore, we demonstrated that the smaller the CH density,
the larger the phase speed inside the CH and the larger the peak values of the second stationary feature.

In this paper, we focus on how different initial density amplitudes influence the kinematics of secondary waves, stationary features, and density depletion. We will demonstrate that there is a correlation between the initial density amplitude of the incoming wave, the amplitudes of the secondary waves, and the peak values of the stationary features.

In Section 2, we introduce the numerical method and describe the initial conditions for our simulations. In Section 3, we present a detailed analysis of the morphology of the secondary waves and the temporal evolution of the stationary features. A comprehensive analysis of the kinematic measurements of the secondary waves with regard to the different initial density amplitudes is presented in Section 4. In Section 5, we combine extreme cases of CH density (large/small) and initial density amplitude (large/small). The outcome of these extreme simulations covers the largest possible range of different phase speeds of the secondary waves and different peak values of the stationary features. Finally, these simulation results are compared to observations. We conclude in Section 6.

2. Numerical Setup

2.1. Algorithm and Equations

We performed 2.5D simulations of fast-mode MHD waves of different initial amplitudes interacting with low density regions by using our newly developed MHD code. This code is based on the so-called Total Variation Diminishing Lax-Friedrichs (TVDLF) method, which is a fully explicit scheme and was first described by Tóth & Odstrcil (1996). We numerically solve the standard MHD equations (see Equations (1)–(5)). By using the TVDLF-method, we achieve second-order accuracy in space and time. This second-order temporal and spatial accuracy is attained by using the Hancock predictor method, which was first described by van Leer (1984). As a limiter function, we apply the so-called Woodward limiter, which guarantees that the method behaves well near discontinuities and that no spurious oscillations are generated (for a detailed description, see van Leer 1977; Tóth & Odstrcil 1996). We use transmissive boundary conditions at the right and left boundaries of the computational box, which is equal to 1.0 both in the x- and y-directions. We perform the simulations using a resolution of $500 \times 300$.

The following set of equations with standard notations for the variables describes the two-dimensional MHD model we use for our simulation.

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0, \quad (1)$$

$$\frac{\partial (\rho \mathbf{v})}{\partial t} + \nabla \cdot (\rho \mathbf{v} \mathbf{v}) - \nabla \times \mathbf{B} + \nabla p = 0, \quad (2)$$

$$\frac{\partial \mathbf{B}}{\partial t} - \nabla \times (\mathbf{v} \times \mathbf{B}) = 0, \quad (3)$$

$$\frac{\partial e}{\partial t} + \nabla \cdot [(e + p) \mathbf{v}] = 0, \quad (4)$$

where the plasma energy $e$ is given by

$$e = \frac{p}{\gamma - 1} + \frac{\rho |\mathbf{v}|^2}{2} + \frac{|\mathbf{B}|^2}{2} \quad (5)$$

and $\gamma = 5/3$ denotes the adiabatic index.

In Figure 1, one can see a vertical cut through the 2D initial conditions (shown in Figure 2) for density, $\rho$, plasma flow velocity, $\mathbf{v}$, and $z$-component of the magnetic field, $B_z$. Figure 1(a) shows an overlay of four different vertical cuts of the 2D density distribution at $y = 0.3$ ($\rho_{IA} = 1.3$), $y = 0.5$ ($\rho_{IA} = 1.5$), $y = 0.7$ ($\rho_{IA} = 1.7$), and $y = 0.9$ ($\rho_{IA} = 1.9$). Moreover, one can see the density drop from $\rho = 1.0$ to $\rho = 0.3$ in the range $0.04 \leq x \leq 0.6$, which represents the CH in our simulation. The background density is equal to 1.0 everywhere. In the range of $0.05 \leq x \leq 0.15$,
the plasma flow velocity, $v_z$, and magnetic field component in the $z$-direction, $B_z$, are functions of $\rho$ (see Figures 1(b) and (c)).

3. Morphology

Figures 3 and 4 show the temporal evolution of the density distribution in four different cases of initial density amplitude, $\rho_{IA}$, for the incoming wave, starting at the beginning of the simulation run at $t = 0$ (see panel (a) in Figure 3) and ending at $t = 0.5$ (see panel (f) in Figure 4). We have plotted four overlayed vertical cuts through the $xz$-plane of our simulations at $y = 0.3$ ($\rho_{IA} = 1.3$, magenta), $y = 0.5$ ($\rho_{IA} = 1.5$, green), $y = 0.7$ ($\rho_{IA} = 1.7$, red), and $y = 0.9$ ($\rho_{IA} = 1.9$, blue) at 12 different times. One can observe the temporal evolution of the incoming wave (hereafter, the primary wave) and the effects of its interaction with the CH. First, we see reflected, traversing, and transmitted waves (all together, hereinafter, referred to as “secondary waves”), which have different phase speeds and amplitudes. Second, one can observe stationary features at the left CH boundary, which exhibit different peak values, depending on the initial density amplitude, $\rho_{IA}$. Third, one can see density depletions of different depths, which are moving in the negative $x$-direction. Additionally, we observe that the primary waves are capable of pushing the left CH boundary in the positive $x$-direction.

3.1. Primary Waves

In Figures 3(a)–(c), one can see how the primary waves with different initial amplitudes are moving in the positive $x$-direction toward the left CH boundary. We observe a decrease of the amplitudes and at the same time a steepening of the primary wave and a shock formation in all four cases (see Figures 3(b)–(c)). Moreover, we find that the larger the initial amplitude, the faster the primary wave moves toward the CH and the faster the evolution of the shock front. Such a behavior is consistent with the MHD wave theory (Vršnak & Lulić 2000).

3.2. Secondary Waves

In Figure 3(d), we can see how the wave for the case $\rho_{IA} = 1.9$ (blue) starts traversing through the CH. Figures 3(e) and (f) show how the other three waves propagate through the CH. We find that the larger the initial amplitude, the larger the amplitude value of the traversing wave.

In Figure 3(d), we also start observing a first reflection for the case $\rho_{IA} = 1.9$ (blue) at $x \approx 0.38$. This first reflective feature is located at the left side of the density depletion in all four cases of different initial amplitude. While this first reflection moves in the negative $x$-direction, its peak value decreases until it reaches a value where it is difficult to distinguish from the background density (see Figures 3(d)–(f) and Figures 4(a)–(f)). We find that the larger the initial amplitude, the larger the amplitude of the first reflection.

There is not only a reflection at the left CH boundary that is moving in the negative $x$-direction, but also a reflection inside the CH. Due to the fact that the amplitudes inside the CH are small compared to the surrounding area, especially in the cases of the reflected waves inside the CH, we zoom in on the region $0.04 \leq x \leq 0.6$ in Figures 5, 6 and 7. Figure 5 shows how the first traversing waves propagate through the CH within $t = 0.19729$ and $t = 0.24824$. We find that the larger the initial amplitude, the larger the amplitude of the traversing wave, i.e., the largest amplitude can be observed for the case $\rho_{IA} = 1.9$ (blue), whereas the smallest amplitude can be found for the case of $\rho_{IA} = 1.34$ (magenta). Furthermore, one can observe that the larger the initial amplitude, the faster the first traversing wave. When this first traversing wave reaches the right CH boundary, one part of the wave leaves the CH while another part gets reflected at the inner CH boundary. This reflected wave (hereafter named the second traversing wave) then moves in the negative $x$-direction inside the CH (see Figure 6). At the time when this second traversing wave reaches the left CH boundary, again one part of the wave gets reflected at the CH boundary inside the CH and propagates in the positive $x$-direction (third traversing wave; shown in Figure 7). Another part of the second traversing wave leaves...
the CH and causes another transmitted wave, which can be seen as an additional bump inside the first transmitted wave (see Figure 8). This second transmitted wave moves together with the first transmitted wave in the positive x-direction until the end of the simulation run at $t = 0.5$. This can only be seen in the case of $\rho_{IA} = 1.9$ (blue) in Figure 8 at $x \approx 0.725$.

Due to the different phase speeds of the primary waves and the waves inside the CH, the traversing waves leave
the CH at different times. Therefore, the larger the initial density amplitude, the earlier we observe the transmitted wave propagating outside the CH in the positive $x$-direction. The first transmitted wave that can be observed is the one with an initial amplitude of $\rho_{IA} = 1.9$ (see Figure 4(a)). In Figures 4(a)–(f), one can see that the larger the initial amplitude, $\rho_{IA}$, the larger the amplitude of the transmitted wave.

Figure 4. Overlay of the temporal evolution of the density distribution for all four initial density amplitudes. Starting when the first wave (blue) leaves the CH at the right CH boundary and ending at the end of the simulation run at $t = 0.5$. The arrows in the figure point toward the different features for the case of $\rho_{IA} = 1.9$ (blue).
Furthermore, we find that the primary wave is capable of pushing the left CH boundary in the positive $x$-direction. We observe that the larger the initial amplitude, the stronger the CH boundary is being pushed to the right.

### 3.3. Stationary Features

In Figure 3(d), we observe a first stationary feature at the left CH boundary for the case $\rho_{IA} = 1.9$ (blue), which appears as a stationary peak at $x \approx 0.4$. This peak occurs in all four cases of different initial amplitude (see Figure 3(e) (red peak) and 3(f) (green peak) at $x \approx 0.4$). For the cases $\rho_{IA} = 1.9$ (blue) and $\rho_{IA} = 1.7$ (red), the peaks can clearly be seen. In order to see and compare all the peak values as well as their lifetimes in all four cases, we zoom in on the area $0.3 \leq x \leq 0.45$ in Figure 9. In this figure, one can see that the larger the initial amplitude, the larger the peak value of the first stationary feature. This stationary peak can be observed first in the case of $\rho_{IA} = 1.9$ (blue) at $x \approx 0.41$, followed by the peaks in the cases $\rho_{IA} = 1.7$ (red), $\rho_{IA} = 1.5$ (green), and $\rho_{IA} = 1.3$ (magenta). The peak values decrease in time in all four cases and move slightly in the positive $x$-direction.

In Figures 4(c)–(e), we find a second stationary feature at the CH boundary. It appears first at $x \approx 0.45$ in Figure 4(c) for the case $\rho_{IA} = 1.9$ (blue), followed by the cases $\rho_{IA} = 1.7$ (red peak at $x \approx 0.44$ in Figure 4(d)) and $\rho_{IA} = 1.5$ (green peak at $x \approx 0.425$ in Figure 4(e)). In order to see the peak also in the case $\rho_{IA} = 1.3$ (magenta) and to compare the other peak values and their lifetimes, we zoom in the area $0.35 \leq x \leq 0.47$ between $t = 0.34092$ and $t = 0.43416$ in Figure 10. In this figure one can see that, as in the case of the first stationary feature, the larger the initial amplitude, the larger the peak value of the second stationary feature. In contrary to the first stationary feature, the second stationary feature is slightly shifted in the negative $x$-direction. The peak values decrease to a value slightly above 1.1 and remain observable while the second reflection moves onward in the negative $x$-direction.

### 3.4. Density Depletion

In Figure 3(d), we observe how a density depletion in the case $\rho_{IA} = 1.9$ (blue) starts evolving at $x \approx 0.4$. It is located at the left side of the first stationary feature and moves in the negative $x$-direction. We find that the larger the initial
its appearance. One can see that the density depletion occurs to study in detail its minimum values and the time of the initial density amplitude, the smaller the minimum value of the density depletion. Figure 11, we zoom in on the area of the density depletion to study in detail its minimum values and the time of its appearance. One can see that the density depletion occurs first in the case $\rho_{IA} = 1.9$ (blue), followed by the cases $\rho_{IA} = 1.7$ (red), $\rho_{IA} = 1.5$ (green), and $\rho_{IA} = 1.3$ (magenta). While moving in the negative $x$-direction, the minimum value of the density depletion decreases.

3.5. 2D Morphology

Figure 12 shows the 2D temporal evolution of the density distribution for nine different time steps, starting at $t = 0$ and ending at the end of the simulation run at $t = 0.49981$. In Figure 12(a), one can see that the initial amplitude increases linearly from $\rho = 1.3$ to $\rho = 1.9$, whereas the CH density has a fixed value of $\rho_{CH} = 0.3$ for all different cases of initial amplitude. In Figure 12(b), we can observe that the waves with larger initial amplitude move faster toward the left CH boundary than the ones with smaller amplitudes. Figure 12(c) shows the evolution of a first stationary feature at the left CH boundary for the waves with large initial amplitude. At the same time, the primary waves with smaller initial amplitude are still moving toward the left CH boundary. In Figure 12(d), we find that the waves with larger initial amplitude have already left the CH and propagate as transmitted waves in the positive $x$-direction (magenta peak), while the waves with small initial amplitude still traverse through the CH. Figures 12(e)–(i) show the evolution and propagation of the density depletion and the reflected wave at the left side of the CH as well as the propagation of the transmitted waves at the right side of the CH in all cases of different initial amplitude, $\rho_{IA}$.

4. Kinematics

4.1. Primary Waves

Figure 13 shows the temporal evolution of the density, $\rho$, plasma flow velocity, $v_x$, position of the wave crest, $\text{Pos}_A$, phase speed, $v_p$, and magnetic field component in the $z$-direction, $B_z$, for the primary waves in every different case of initial amplitude, $\rho_{IA}$. In Figure 13(a), we observe that the amplitude of the density remains approximately constant at their initial values until the time when the shock is formed and the density amplitude of the primary wave starts decreasing (see Vršnak & Lulić 2000), i.e., at $t \approx 0.03$ (blue), $t \approx 0.04$ (red), and $t \approx 0.055$ (green). For the case of $\rho_{IA} = 1.3$ (magenta), a decrease of the amplitude of the primary can hardly be observed, as expected for low-amplitude wave (Warmuth 2015). One can see that the larger the initial amplitude, $\rho_{IA}$, the stronger the decrease of the primary wave’s amplitude, which is consistent with observations (Warmuth & Mann 2011; Muhr et al. 2014; Warmuth 2015). The amplitudes decrease to values of $\rho \approx 1.6$ (blue), $\rho \approx 1.5$ (red), and $\rho \approx 1.4$ (green) until the
Figure 9. Zoom-in of the area of the first stationary feature in the range $0.3 \leq x \leq 0.45$ for the cases $\rho_{IA} = 1.9$ (blue), $\rho_{IA} = 1.7$ (red), $\rho_{IA} = 1.5$ (green), and $\rho_{IA} = 1.3$ (magenta). Starting at $t = 0.19176$ and ending at $t = 0.27179$. The arrows in the figure point at the peak value of the first stationary feature in the case of $\rho_{IA} = 1.9$ (blue).

Figure 10. Zoom-in of the area of the second stationary feature in the range $0.35 \leq x \leq 0.47$ for the cases $\rho_{IA} = 1.9$ (blue), $\rho_{IA} = 1.7$ (red), $\rho_{IA} = 1.5$ (green), and $\rho_{IA} = 1.3$ (magenta). Starting at $t = 0.34092$ and ending at $t = 0.43416$. The arrows in the figure point at the peak value of the second stationary feature in the case of $\rho_{IA} = 1.9$ (blue).
primary wave starts entering the CH. Due to the fact that the waves with larger initial amplitude enter the CH earlier than those with small initial amplitude, we can see in Figure 13(a) that the tracking of the parameters of the faster waves stops at an earlier time than the one for the slower waves. A similar behavior to the one of the density, $\rho$, can be observed for the plasma flow velocity, $v_x$, in Figure 13(b) and the magnetic field component, $B_z$, in Figure 13(e). Here, the amplitudes decrease from $v_x = 0.75$, $B_z = 1.9$ (for $\rho_{IA} = 1.9$, blue), $v_x = 0.6$, $B_z = 1.7$ (for $\rho_{IA} = 1.7$, red), $v_x = 0.45$, $B_z = 1.5$ (for $\rho_{IA} = 1.5$, green), and $v_x = 0.27$, $B_z = 1.3$ (for $\rho_{IA} = 1.3$, magenta) to $v_x = 0.55$, $B_z = 1.6$ (for $\rho_{IA} = 1.9$, blue), $v_x = 0.46$, $B_z = 1.5$ (for $\rho_{IA} = 1.7$, red), $v_x = 0.36$, $B_z = 1.4$ (for $\rho_{IA} = 1.5$, green), and $v_x = 0.25$, $B_z = 1.25$ (for...
larger the initial amplitude, $\rho_{IA}$, the faster the traversing wave propagates through the CH. In detail, this means that the amplitudes for the phase speed, $v_w$, start at $v_w \approx 2.38$ (for $\rho_{IA} = 1.9$, blue), $v_w \approx 2.35$ (for $\rho_{IA} = 1.7$, red), $v_w \approx 2.33$ (for $\rho_{IA} = 1.5$, green), and $v_w \approx 2.3$ (for $\rho_{IA} = 1.3$, magenta), and decrease to $v_w \approx 2.3$ (for $\rho_{IA} = 1.9$, blue), $v_w \approx 2.24$ (for $\rho_{IA} = 1.7$, red), $v_w \approx 2.14$ (for $\rho_{IA} = 1.5$, green), and $v_w \approx 2.05$ (for $\rho_{IA} = 1.3$, magenta). Figure 14(c) shows how the traversing waves propagate in the positive x-direction in all four cases of different initial amplitude, $\rho_{IA}$.

Figure 15 describes the temporal evolution of the parameters of the transmitted waves. In Figure 15(a), we observe that the larger the initial amplitude, $\rho_{IA}$, the larger the amplitude of the transmitted wave. More specifically, the density values decrease from $\rho \approx 1.48$ (for $\rho_{IA} = 1.9$, blue), $\rho \approx 1.4$ (for $\rho_{IA} = 1.7$, red), $\rho \approx 1.3$ (for $\rho_{IA} = 1.5$, green), and $\rho \approx 1.22$ (for $\rho_{IA} = 1.3$, magenta) to $\rho \approx 1.35$ (for $\rho_{IA} = 1.9$, blue), $\rho \approx 1.31$ (for $\rho_{IA} = 1.7$, red), $\rho \approx 1.25$ (for $\rho_{IA} = 1.5$, green), and $\rho \approx 1.18$ (for $\rho_{IA} = 1.3$, magenta) at the end of the simulation run at $t = 0.5$. Furthermore, we observe that the larger the initial amplitude, $\rho_{IA}$, the earlier the transmitted wave appears at the right CH boundary and starts propagating in the positive x-direction. Analogous to the density, $\rho$, the plasma flow velocity, $v_w$, and magnetic field in the z-direction, $B_z$, also decrease with time (see Figures 15(b) and (e)).

Figure 15(c) shows how the transmitted wave propagates in the positive x-direction in every case of different initial amplitude, $\rho_{IA}$.

Figure 15(d) describes how the phase speed of the different transmitted waves decreases with time. We find that the larger the initial amplitude, $\rho_{IA}$, the faster the transmitted waves propagate in the positive x-direction, i.e., the values for the phase speed, $v_w$, decrease from $v_w \approx 1.39$ (for $\rho_{IA} = 1.9$, blue), $v_w \approx 1.27$ (for $\rho_{IA} = 1.7$, red), $v_w \approx 1.2$ (for $\rho_{IA} = 1.5$, green), and $v_w \approx 1.18$ (for $\rho_{IA} = 1.3$, magenta) at the time when the transmitted wave starts appearing at the right CH boundary, to $v_w \approx 1.27$ (for $\rho_{IA} = 1.9$, blue), $v_w \approx 1.27$ (for $\rho_{IA} = 1.7$, red), $v_w \approx 1.23$ (for $\rho_{IA} = 1.5$, green), and $v_w \approx 1.05$ (for $\rho_{IA} = 1.3$, magenta) at the end of the simulation run. The fluctuations at the beginning of Figures 15(b) and (e) result from the resolution in the tracking algorithm for $v_w$ and $B_z$.

### 4.3. Stationary Features

In Figure 16, we analyze the evolution of the first stationary feature for all different cases of initial density amplitude, $\rho_{IA}$. This feature appears first for the case $\rho_{IA} = 1.9$ (blue) at $t \approx 0.2$, followed by the stationary features in the cases $\rho_{IA} = 1.7$ (red), $\rho_{IA} = 1.5$ (green), and $\rho_{IA} = 1.3$ (magenta). In Figure 16(a), one can see that the larger the initial density amplitude, $\rho_{IA}$, the larger the peak value of the first stationary feature, i.e., we observe the largest peak for the case $\rho_{IA} = 1.9$ (blue) and the smallest peak value for the case $\rho_{IA} = 1.3$ (magenta). The density values decrease from $\rho \approx 1.3$ (for $\rho_{IA} = 1.9$, blue), $\rho \approx 1.24$ (for $\rho_{IA} = 1.7$, red), $\rho \approx 1.18$ (for $\rho_{IA} = 1.5$, green), and $\rho \approx 1.11$ (for $\rho_{IA} = 1.3$, magenta) to $\rho \approx 1.08$ (for $\rho_{IA} = 1.9$, blue), $\rho \approx 1.05$ (for $\rho_{IA} = 1.7$, red), $\rho \approx 1.04$ (for $\rho_{IA} = 1.5$, green), and $\rho \approx 1.02$ (for $\rho_{IA} = 1.3$, magenta). Analogous to the temporal evolution of the density, $\rho$, the amplitudes for the plasma flow velocity, $v_w$, and the magnetic field component in the z-direction, $B_z$, decrease with time (see Figures 16(b) and (e)). Figure 16(c) shows that the first stationary feature moves slightly in the positive x-direction. In Figure 16(d), we find that the larger the

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**Figure 13.** From top to bottom: temporal evolution of the primary wave’s density, plasma flow velocity, position of the wave crest, phase velocity, and magnetic field for the cases $\rho_{IA} = 1.9$ (blue), $\rho_{IA} = 1.7$ (red), $\rho_{IA} = 1.5$ (green), and $\rho_{IA} = 1.3$ (magenta). Starting at the beginning of the simulation run and ending when the slowest wave (magenta) has entered the CH.

**Figure 14.** In Figure 14(a), we find that the traversing waves propagate with a low amplitude through the CH. Moreover, one can see that the larger the initial amplitude, $\rho_{IA}$, the larger the amplitude inside the CH. When the wave enters the CH, it takes a short time until the amplitude achieves its highest value from where it starts decreasing slightly while propagating through the CH, i.e., $\rho \approx 0.42$ (for $\rho_{IA} = 1.9$, blue), $\rho \approx 0.4$ (for $\rho_{IA} = 1.7$, red), $\rho \approx 0.38$ (for $\rho_{IA} = 1.5$, green), and $\rho \approx 0.36$ (for $\rho_{IA} = 1.3$, magenta) decrease to $\rho \approx 0.41$ (for $\rho_{IA} = 1.9$, blue), $\rho \approx 0.39$ (for $\rho_{IA} = 1.7$, red), $\rho \approx 0.37$ (for $\rho_{IA} = 1.5$, green), and $\rho \approx 0.357$ (for $\rho_{IA} = 1.3$, magenta) until the traversing waves leave the CH and gets partly reflected at the right CH boundary at the same time. For the plasma flow velocity, $v_w$, and the magnetic field component in the z-direction, $B_z$, we find a similar decreasing behavior (see Figures 14(b) and (e)). In Figure 14(d), we observe that the
initial density amplitude, $\rho_{IA}$, the faster the first stationary feature gets shifted in the positive $x$-direction.

The kinematics of the second stationary feature are presented in Figure 17. The density plot in Figure 17(a) shows a correlation between the initial density amplitude, $\rho_{IA}$, and the peak values of the second stationary feature. Similar to the first stationary feature, we observe that the larger the initial amplitude, $\rho_{IA}$, the larger the peak values of the density of the second stationary feature (see Figure 17(a)), i.e., $\rho \approx 1.15$ (for $t \approx 0.35$ and $\rho_{IA} = 1.9$), $\rho \approx 1.09$ (for $t \approx 0.39$ and $\rho_{IA} = 1.7$), $\rho \approx 1.08$ (for $t \approx 0.42$ and $\rho_{IA} = 1.5$), and $\rho \approx 1.06$ (for $t \approx 0.45$ and $\rho_{IA} = 1.3$). The amplitudes of $B_z$ are similar to the ones of the density (see Figure 17(e)). Due to the fact that the shift of this feature in the negative $x$-direction is extremely small (see Figure 17(c)), the plasma flow velocity, $v_x$, and the phase speed, $v_w$, are close to zero (see Figures 17(b) and (d)).

4.4. Density Depletion

In Figure 18, we present the temporal evolution of the density depletion for all cases of different initial amplitude, $\rho_{IA}$. In Figure 18(a), we observe that this feature occurs first for the case $\rho_{IA} = 1.9$ (blue) at $t \approx 0.25$, followed by the cases $\rho_{IA} = 1.7$ (red), $\rho_{IA} = 1.5$ (green), and $\rho_{IA} = 1.3$ (magenta). We see that the larger the initial amplitude, $\rho_{IA}$, the smaller the minimum value of the density depletion, i.e., the final minimum values are $\rho \approx 0.83$ (for $\rho_{IA} = 1.9$, blue), $\rho \approx 0.86$ (for $\rho_{IA} = 1.7$, red), $\rho \approx 0.9$ (for $\rho_{IA} = 1.5$, green), and $\rho \approx 0.93$ (for $\rho_{IA} = 1.3$, magenta). An analogous behavior to the density evolution can be observed for the plasma flow velocity, $v_x$, and the magnetic field component in the $z$-direction, $B_z$ (see Figures 18(b) and (e)). In Figure 18(c), one can see how the density depletion is moving in the negative $x$-direction. Figure 18(d) shows that the larger the initial density amplitude, $\rho_{IA}$, the larger the phase speed at which the depletion is moving in the negative $x$-direction.

5. Extreme Values

Pantschitsch et al. (2018) analyzed how the CH density influences the amplitudes and the phase speed of the secondary waves. In this paper, we focused on the influence of the initial amplitude of the incoming wave on the parameters of the secondary waves. By combining the results of Pantschitsch et al. (2018) and those we obtained in this paper, we find first, that the combination of a small CH density and a large initial density amplitude leads to a large phase speed of the secondary waves. Second, we observed that the larger the CH density and the larger the initial wave amplitude, the larger the peak values for the first stationary feature. Hence, we will simulate and analyze the extreme cases for the phase speed of the secondary waves as well as the peak values of the first stationary feature.

5.1. Comparison of Secondary Waves—Phase Speed

We assume two extreme cases for the phase speed. For the secondary waves, the largest phase speed can be achieved if we assume a large initial amplitude, $\rho_{IA}$, (corresponding to $\rho_{IA} = 1.9$) and a small CH density, $\rho_{CH}$ (corresponding to $\rho_{CH} = 0.1$).
The smallest phase speed, on the other hand, is a result of combining a small initial amplitude, $\rho_{IA}$ (corresponding to $\rho_{IA} = 1.3$) with a large CH density, $\rho_{CH}$ (corresponding $\rho_{CH} = 0.5$). In Figure 19, one can see how the density amplitudes for the two extreme cases evolve with time. Figure 20 shows a comparison of the simulated extreme cases with observations of Kienreich et al. (2013) and Olmedo et al. (2012).

In the upper panel of Figure 20 where we compare our simulation results to the observations in Kienreich et al. (2013) one can see how the primary waves propagate with different phase speeds toward the CH (blue shaded area). The stars (black) represent the primary wave of the observations and the simulation at the same time; we assume that the observational phase speed coincides, first, with the simulation phase speed of extreme case No. 1, and, second, with the simulation phase speed of extreme case No. 2. When the primary wave enters the CH, we observe that the simulated phase speed increases (blue solid lines). Subsequently, the phase speed decreases, when the waves leave the CH and propagate further as transmitted waves (green solid lines). Moreover, we can see that the phase speed of the observed reflected wave (red stars) is smaller than the extreme values of the phase speed of the simulated reflected waves (red solid lines). In order to get the percentage of the phase speed drop in the observations, we compared the mean velocity of the primary and the reflected wave in Kienreich et al. (2013). In our simulations, the mean phase speed of the reflected waves is smaller by approximately 39% relative to the incoming speed in extreme case No. 1 and 28% in extreme case No. 2, whereas in the observations of
Kienreich et al. (2013) we find an average difference of about 48% (magenta stars in the upper panel). This deviation of the phase speed can be explained by the constraints we have in the simulation. First, we do not consider refraction in our study, i.e., every primary wave approaches the CH boundary exactly perpendicularly. Second, we perform 2.5D simulations, i.e., the wave is not able to escape in the vertical direction when interacting with the CH. Hence, the smaller drop in the phase speed of the simulated reflected waves, compared to the observed ones, is consistent with what we expect due to our simulation constraints.

In the lower panel of Figure 20, we see the same simulated extreme cases for the phase speed as in the upper panel, but this time, compared to the observations of Olmedo et al. (2012). Again, we assume that the initial phase speed in the observations phase speed coincides, first, with the simulation phase speed of extreme case No. 1, and, second, with the simulation phase speed of extreme case No. 2. The phase speed of the reflected waves in these observations decreases by approximately 58% (magenta stars in the lower panel), which is again a larger drop than in the simulations. We find that the phase speed of the observed traversing wave (blue stars) is smaller than the simulated ones; the same is true for the observed phase speed of the transmitted wave (green stars). In the simulations, the phase speed of the traversing waves is about 130% (extreme case No. 1) and 24% (extreme case No. 2) larger than the phase speed of the primary waves. The observational phase speed changes were obtained by comparing the mean velocity of the primary wave with the mean velocity of reflected, traversing, and transmitted waves in Olmedo et al. (2012). Here the phase speed increases only by about 3% (blue stars) when the primary wave enters the CH. In the observations, the phase speed of the transmitted wave is smaller by approximately 64% (green stars) relative to the incoming speed, whereas in the simulations the phase speed of the transmitted wave is smaller by about 26% relative to the incoming speed in extreme case No. 1 and 19% in extreme case No. 2 (green solid line). Again, this deviation can be explained by the constraints we apply in our simulation. We assume a homogeneous magnetic field, which does not reflect the complex magnetic field structure inside an actual CH. Therefore, the faster phase speed of the traversing and transmitted waves in the simulation is compatible with observations.

5.2. Comparison of First Stationary Features—Density

Similar to the comparison of extreme values for the secondary waves, we assume two different extreme cases for the first stationary feature. In order to achieve the largest peak value for this feature, we combine a large initial density amplitude, \( \rho_{IA} = 1.9 \), with a large CH density, \( \rho_{CH} = 0.5 \). A small peak value for the first stationary feature can be achieved by combining a small initial density amplitude, \( \rho_{IA} = 1.3 \), with a small CH density, \( \rho_{CH} = 0.1 \). In Figure 21, one can see the temporal evolution of these two extreme cases and how the first stationary feature reaches its smallest and its largest values. Figure 22 shows how the peak values of the density for both extreme cases evolve with time. We find that the lifetime of the first stationary feature is between \( t \approx 0.08 \) and \( t \approx 0.16 \) in our simulations, which corresponds to approximately 10 and 20 minutes in real-time if we assume an Alfvén speed of approximately 300 km s\(^{-1}\) and a CH width of about 300 Mm. This value shows good agreement with observations, where authors report about a lifetime of stationary brightenings of about 15 minutes (Delanné & Aulanier 1999). It is also observed that a bright front can lie at the same location even for several hours (Delanné 2000).
Figure 20. Comparison between the simulated extreme cases of the secondary waves and the observations of Kienreich et al. (2013; upper panel) and Olmedo et al. (2012; lower panel). In both panels the black line with stars represents, at the same time, the speed of the two extreme cases of the simulated primary wave as well as the speed of the incoming wave in the observations. The other lines with stars denote the speed in the observations, whereas the solid lines represent the speeds of the simulated waves.
6. Conclusions

We present simulation results of different fast-mode MHD waves interacting with a CH using a newly developed 2.5 MHD code. In Piantschitsch et al. (2017), we found that the interaction of an MHD wave with a CH leads to the evolution of different secondary waves (reflected, traversing, and transmitted waves) and the formation of stationary features. In that study, we assumed fixed values for the CH density and the initial density amplitude. In Piantschitsch et al. (2018),

![Morphology - Extreme Cases / 1st Stationary Feature](image)

Figure 21. Temporal evolution of the density for the two extreme cases of the stationary features. The green line represents the case that combines a large initial amplitude ($\rho_{IA} = 1.9$) with a large CH density ($\rho_{CH} = 0.5$), which means a small density drop compared to the background density. The magenta line denotes a case that combines a small initial amplitude ($\rho_{IA} = 1.3$) with a small CH density ($\rho_{CH} = 0.1$).

![1st Stationary Feature / Extreme Cases](image)

Figure 22. Comparison of the lifetime of the extreme density peak values for the first stationary feature. If we assume an Alfvén speed of approximately 300 km s$^{-1}$ and a CH width of about 300 Mm the lifetime of the first stationary feature in our simulation corresponds to approximately 10 minutes (green line) and 20 minutes (magenta line). These results are in agreement with observations where authors report about a lifetime of stationary brightenings of about 15 minutes (Delannée & Aulanier 1999).
we analyzed the influence of different CH densities on the parameters of secondary waves and stationary features.

In this paper, we focus on the comparison of the cases with different initial amplitude of the incoming wave. We find correlations between the initial density amplitude, on the one hand, and the parameters of secondary waves as well as the peak values of the stationary features on the other hand. Moreover, we analyzed extreme cases of the phase speed of secondary waves and the lifetime of stationary features and subsequently compared the obtained simulation results to observations. The main results are summarized as follows.

1. The kinematic analysis of the traversing and the transmitted wave has shown that the larger the initial amplitude of the primary wave, the larger the amplitudes of density, magnetic field component in the z-direction, plasma flow velocity, and phase speed of both, traversing and transmitted waves (see Figures 3, 4, 14 and 15).

2. For the reflected wave, we have found that the larger the initial amplitude of the primary wave, the larger the mean phase speed of the reflection.

3. For the first and the second stationary features, we observe that the larger the initial amplitude of the primary wave, the larger the peak values of density and magnetic field component in the z-direction of these features. Moreover, we observe that the first feature moves slightly in the positive x-direction, whereas the second stationary feature is somewhat shifted in the negative x-direction (see Figures 3, 4, 16, and 17).

4. The simulation results for the density depletion show that the larger the initial amplitude of the primary wave, the smaller the minimum value of the density depletion (see Figures 4 and 18).

5. By combining the results of Piantschitsch et al. (2018) with the results of this paper, we find that the combination of a large initial amplitude with a small CH density leads to the largest phase speeds of the secondary waves and to the lowest minimum value of the density depletion (see Figure 20).

6. A combination of a large initial amplitude with a large CH density, on the other hand, leads to the largest peak values of the first stationary feature (see Figure 22).

We compared our simulation results to observations of secondary waves in Kienreich et al. (2013) and Olmedo et al. (2012). The fact that the phase speed of the secondary waves in the observations is slightly smaller than that in the simulations can be explained, first, by the simplified magnetic field structure of the CH in the simulations, which does not reflect the actual situation in the observations. Second, in the simulation, the wave is approaching exactly perpendicularly to the CH boundary at every point and hence cannot be refracted. Third, we perform 2.5D simulations, i.e., the wave is not capable of escaping in the vertical direction. Nonetheless, many aspects of the simulations are consistent with the observations.

Comparisons of the lifetime of the first stationary feature with the lifetime of stationary bright fronts at CH boundaries in actual observations show good agreement. Assuming an Alfvén speed of approximately 300 km s$^{-1}$ and a CH width of about 300 Mm leads to a stationary feature lifetime between 10 and 20 minutes in the simulation. Observations report about a lifetime of approximately 15 minutes for stationary brightenings (Delannée & Aulanier 1999).

Additionally, Kienreich et al. (2013) have found reflected features that consist of a bright lane followed by a dark lane in base-difference images. These findings correspond to the first reflection and the density depletion in our simulation.

However, we have to be aware that our simulations represent a simplified model of the actual situation in the observations, i.e., we have constraints like a homogenous magnetic field, a pressure that is equal to zero over the whole computational box and a simplified shape of the CH.

Overall, independent from the choice of initial CH density (see Piantschitsch et al. 2018) or initial density amplitude of the incoming wave, our simulations show that the interaction of a fast-mode MHD wave with a CH leads to the formation of secondary waves and to the appearance of stationary features at the CH boundary. Both findings strongly support the theory that coronal waves are fast-mode MHD waves.

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