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Plasma Evolutions Around A Solar Coronal 3D Magnetic Null Point

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Abstract. It is investigated how the plasma evaluates due to the propagation of the nonlinear Alfvén wave. Magnetic null points that are detected in the solar corona have 3D structures which are prevalent in the solar atmosphere. In this study, we consider the real 3D structure with a 3D magnetic null point. The shock-capturing Godunov-type PLUTO code is used to solve the resistive magnetohydrodynamic (MHD) set of equations in the context of wave-plasma energy transfer to find out how the plasma evaluates. An initially symmetric Alfvén pulse at a specific distance from a magnetic null-point is kicked towards the isothermal null-point. Alfvén wave propagation around a 3D magnetic null point results in magnetoacoustic waves perturbations which propagate towards the null point and refract around the null point. It is found that nonlinear Alfv ´en wave propagation around a 3D magnetic null point results in plasma density perturbations due to the compressible magnetoacoustic waves perturbations.

Keywords: Magnetohydrodynamics, Alfvén wave, PLUTO code, Magnetic null point.

1 Introduction

The coronal heating problem is one of the main unsolved problems in solar physics. There are many competing theories proposed, such as magnetic reconnection models (including micro- and nanoflares) and wave heating models involving phase mixing and resonant absorption. The structure and dynamics of the solar corona is dominated by the magnetic field, and the MHD wave behaviour is strongly influenced by the surrounding magnetic structure. Therefore, it is important to note the topology of the coronal magnetic field and to take it into account in the wave evolution models. Using photospheric magnetograms as boundary conditions, potential field extrapolations of the coronal magnetic field show two important features of the magnetic topology, viz. magnetic null points and separatrices.

At the magnetic null points, the strength of the magnetic field (and thus the Alfvén speed) is zero. The existence of magnetic null points in the coronal magnetic field has been proved via magnetic field extrapolations, see e.g. [1]. These null points play a key role in many processes of the solar atmosphere, such as magnetic reconnection [2], oscillatory reconnection [3] and in CME onset processes [4, 5]. The complexity of the magnetic flux distribution defines the number of the resultant null points, so that tens or thousands of them are estimated to be present at any time in the solar corona [6] and [7].

Magnetic null points in the solar atmosphere have a significant role in the study of the Sun. Astrophysical magnetic fields are three−dimensional and therefore to comprehend the plasma heating process we have to pursue 3D magnetic fields structures. [8, 9] and [10] studied the current accumulation at the null point, the spine or the fan plane in 3D regime without investigation the the behavior of the waves. [11] studied the behavior of the Alfvén wave near the 3D magnetic null point via WKB approximation. It was found that the Alfvén wave moves at the equilibrium Alfvén speed along the magnetic field lines and focuses along the fan and spine of the magnetic null point as 2D results. Besides, the local properties of a perturbed 3D magnetic null point has been studied in the linear regime for cold plasma [12].

The three fundamental wave modes in magnetohydrodynamic (MHD) systems are Alfvén wave, and fast and slow magnetoacoustic waves. The presence of these waves in the solar corona has been demonstrated by many observations: for example Alfvén waves by [13], and fast and slow magnetoacoustic waves by [14]. Interactions of these MHD waves with the ubiquitous magnetic null points are an inevitable fundamental aspect of the dynamic solar atmosphere. The propagation of MHD waves in the neighborhood of magnetic null points has been studied extensively in simple 2D models, and also in real 3D structure for instance by [15, 16, 17, 18, 19, 20, 21, 22]. As a result, the Alfvén waves accumulate along the separatrices without crossing them, whereas the fast waves refract along the Alfvén-speed profile and accumulate at the null point. Therefore, these regions are identified as locations for potential heating by ohmic wave dissipation and are implicated as a possible mechanism for localized heating events. One possible process for coronal heating is the presence and dissipation of waves in different coronal structures. The coronal magnetic energy is somehow concentrated in the closed magnetic field structures and different mechanisms such as magnetic reconnection can release this energy along the open magnetic field, contributing to the solar wind generation.

Transporting energy and heating different layers of the solar atmosphere and acceleration of the solar wind associated to the magnetohydrodynamic (MHD) waves in various studies [23, 24]. Among three MHD modes, Alfvén waves can carry their energy along the magnetic field lines to higher atmospheric layers [25, 26]. The studies of the Alfvén waves has significantly developed due to their observational evidence in the solar atmosphere [27, 28]. [29] via observational investigations reported by [30] indicated that rotational motions observed in the lower layers of the solar atmosphere generated magnetic twister like motions in the transition region and corona. Instead, the tornado–like motions were decried as torsional Alfvén waves.

The remainder of this paper is organized as follows: in Section 2, we outline the basic equations and discuss the initial setup used in the simulation; in Section 3, we discuss the behaviour of Alfvén wave near a 3D magnetic null point and its following compressible magnetoacoustic waves perturbations and also their effect on variation of the plasma density. Finally, in Section 4, we provide a brief conclusion and outlook.

2 Experimental and numerical setup

The MHD theory is implemented to model the macroscopic dynamics of MHD waves propagating in a plasma medium that includes a 3D magnetic null-point. The resistive MHD equations are used and formulated in the following form

$$\rho\left[\frac{\partial \mathbf{V}}{\partial t}+(\mathbf{V}\cdot\nabla)\mathbf{V}\right]=\left(\frac{1}{\mu}\nabla\times\mathbf{B}\right)\times\mathbf{B}-\nabla P, \tag{1}$$

$$\frac{\partial \mathbf{B}}{\partial t}=\nabla\times(\mathbf{V}\times\mathbf{B})+\eta\nabla^2\mathbf{B}, \tag{2}$$

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{V}) = 0, \tag{3}$$

$$\frac{\partial P}{\partial t} + (\mathbf{V} \cdot \nabla) P = -\gamma P \nabla \cdot \mathbf{V}, \tag{4}$$

where ρ, $\mathbf{V}$, $\mathbf{B}$, and P represent, respectively, the mass density, plasma velocity, magnetic field and plasma pressure. The constants μ and γ denote the magnetic permeability and the ratio of the specific heats, where we have $\mu = 4\pi \times 10^{-7}$ Hm^{-1} and $\gamma = 5/3$. Besides, We use outflow boundary conditions, which means that all of quantities have zero gradient at the boundaries of the computational domain.

A static ($\mathbf{V}_0 = \mathbf{0}$) background plasma is considered with a magnetic field given by

$$\mathbf{B}_0 = [x, \epsilon y, -(\epsilon + 1) z]. \tag{5}$$

Whereas, we want to study about the behaviour of the MHD waves around the 3D magnetic null point, we introduced a magnetic−flux based coordinate system that each direction described a definite MHD wave mode.

The experimental setup of the present study is solved in the context of MHD theory. The MHD equations ($1-4$) are solved numerically using the high-resolution shock-capturing code PLUTO, that is an appropriate and robust tool for studying nonlinear dynamics of magnetized fluid [31]. This code is appropriate for explicit time-dependent computations, where we applied the Godunov method (approximate Riemann solver) [32, 33, 34].

The PLUTO code is designed to solve a system of conservation laws on structured meshes; based on a finite-difference or finite-volume methods. Most studies prior to this work have used the Lagrangian representation. However, in order to take into account the dissipative effects together with the entropy, the Godunov-type shock-capturing Riemann solver schemes are implemented in the present study. The PLUTO code enables solving full nonlinear MHD equations in one to three dimensions. In the present study, the resistive MHD equations are solved in 3D.

The magnetic field $\mathbf{B}$ is defined on the cell faces in order to keep $\nabla \cdot \mathbf{B} = 0$. We simulated the plasma dynamics in a domain with $(-10, 10) \times (-10, 10) \times (-10, 10)$ Mm and $1400 \times 1400 \times 1400$ grid points. Since our main goal is to study the behaviour of waves in the vicinity of a magnetic null-point, a stretched grid has been used to concentrate the majority of the grid points close to the null-point. Therefore, we set $1200 \times 1200 \times 1200$ grid points in the numerical domain $(-6, 6) \times (-6, 6) \times (-6, 6)$ Mm with an effective resolution of $\delta x \approx \delta y \approx \delta z \approx 1/100$ Mm.

3 Results

The propagation of the nonlinear Alfvén wave leads to the creation of secondary waves. This is due to nonlinear coupling of the transverse variables to the longitudinal ones in the MHD equations. Total pressure perturbation generates longitudinal (slow magnetosonic) waves and fast waves which are polarized in the direction perpendicular to the flux surfaces [22]. The initial torsional Alfvén wave excites flows with two other velocity components, the parallel component (to the magnetic field) and the normal velocity (perpendicular to the flux surfaces) that correspond to, respectively, slow and fast magnetoacoustic waves [21]. The creation of the normal/perpendicular perturbations can be ascribed to the nonlinear ponderomotive force affiliated to the gradients of the perpendicular perturbed Alfvén speed [35]. On the other hand, generation of the parallel flows may be associated to the nonlinear ponderomotive force that is induced by the gradients of parallel perturbed Alfvén

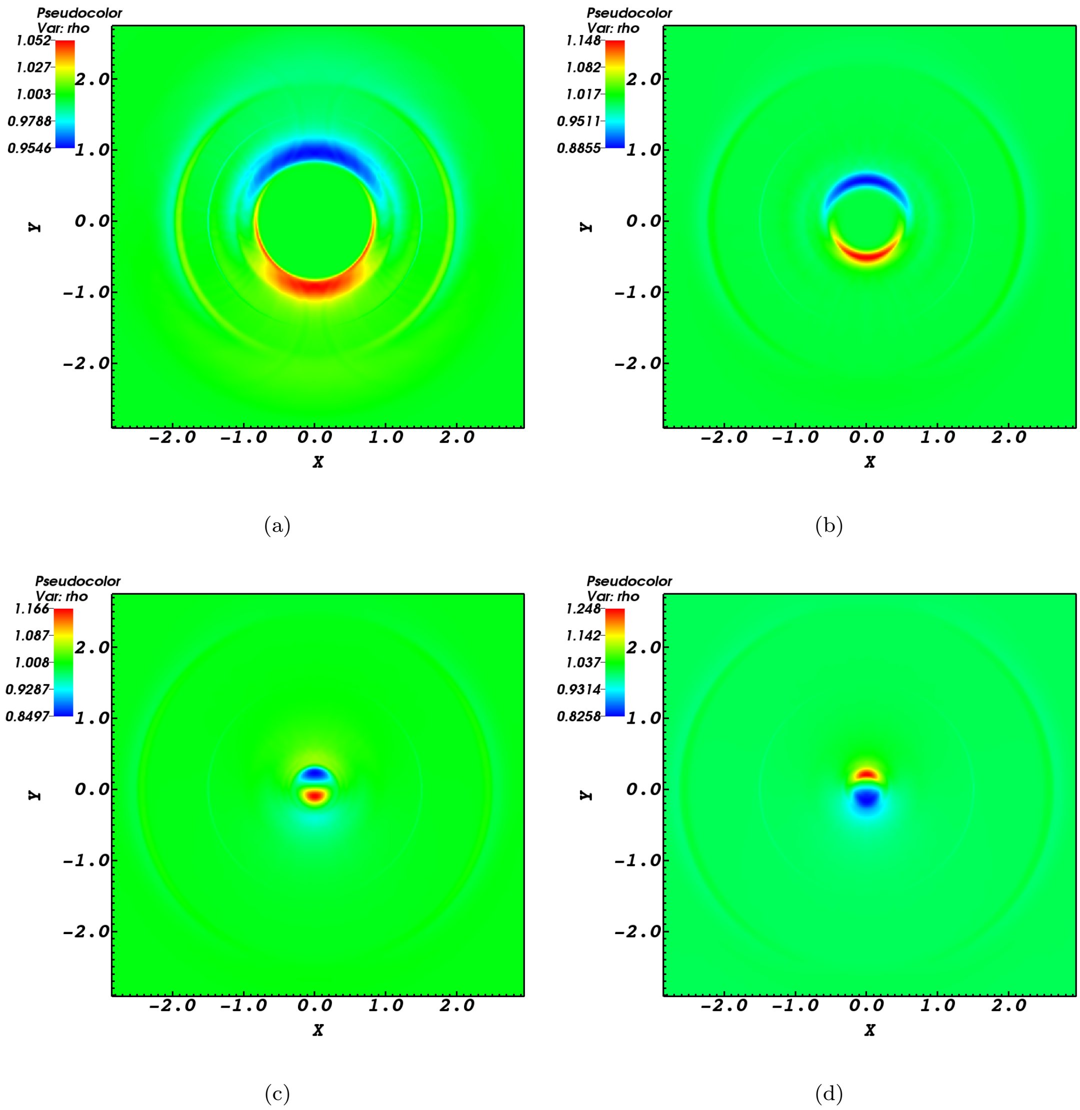

Figure 1: Snapshots of the plasma density at t = 0.3 s, t = 0.5 s, t = 0.7 s and t = 0.8 s which are respectively correspond to the panels (a) to (d).

speed. The modification of the local Alfvén speed is due to the ponderomotive excitation of magnetoacoustic waves that affects the Alfvén wave itself and leads to the wave steepening.

As a matter of fact, the key element in the nonlinear evolution of MHD waves is the ponderomotive force that is related to the variation of the absolute value of the magnetic field. This alteration modifies the gradient of the magnetic pressure that derives plasma flows and, hence, changes the density of the plasma, as we see in Figure 1 that demonstrates perturbations of plasma density. Panels (a) to (d) of Figure 1 depict that due to the refraction of the magnetoacoustic waves around the null point which is one of the main characteristics of these waves, plasma density profile has the value around the null point.

4 Discussion

There are complex nonlinear interactions between the magnetic field and the plasma in the solar corona. This produces various processes such as particle acceleration, shock waves, instabilities and magnetic reconnection. The key effect of the nonlinear evolution, however, is the ponderomotive force which is associated with the change into the magnitude of the magnetic field. This force leads to the variations of the magnetic pressure and also plasma density. The induced phase mixing effect due to the resulting changes in the local values of the Alfvén speed, results in an Alfvén wave self-interaction [36] and [37].

Alfvén wave pulse has been considered and initiated by perturbing the z-component of the velocity field. The Alfvén wave produces nonlinear perturbations in the $x-y$ plane where the nonlinear wave is created and directed towards the null-point in the perpendicular direction, normal to the flux surfaces. Although this wave is a transverse wave like its kicker, the Alfvén wave, it's propagation towards the null-point is independent of the Alfvén wave. This fast magnetoacoustic wave eventually accumulates at the null-point, see also [38]. The density perturbations are signatures of the induced compressive perturbations (by the Alfvén pulse). Therefore, it is found that Alfvén wave propagation could result in plasma density variations due to the magnetoacoustic waves perturbations.

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