

EFFECTS OF MHD SLOW SHOCKS PROPAGATING ALONG THE IO FLUX TUBE

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Abstract

In our study, we focus on a mechanism of the interaction between Io and Jupiter based on MHD slow shocks propagating from Io towards Jupiter along the magnetic flux tube. These MHD slow shocks are results of plasma perturbations near Io considered as a source of ionized particles. The propagation of the slow shocks is calculated along a given magnetic flux tube from Io to Jupiter. The “magnetic string” equations in frozen-in coordinates are used to describe the plasma flow along the magnetic tube. An important aspect of this problem is that the total pressure increases by a factor of 10^4 , whereas the cross section of the magnetic flux tube decreases by a factor of 10^2 . The result is obtained that the plasma velocity after the shock front substantially increases towards Jupiter with increasing magnetic pressure. This effect is stronger when the initial plasma pressure enhancement is larger.

1 Introduction

It is generally believed that the main factors of the plasma torus – Io – Jupiter electrodynamic interaction are Alfvén wings which are standing Alfvén waves attached to the satellite [Neubauer, 1980]. However, besides these Alfvén waves, there also exist slow magnetosonic waves which are caused by the interaction of Io with the torus plasma. The importance of the slow mode perturbations was pointed out by Wright and Schwartz [1990], Linker et al. [1991], and Kopp [1996]. The aim of our paper is to model the propagation of a MHD slow wave from the point of its generation near Io until the Jovian ionosphere.

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Pressure pulses which are responsible for the slow mode generation can be produced either by volcanic outbursts at Io or created in the course of torus plasma flow around Io. An important factor is the mass loading which can provide a local enhancement of the plasma pressure near Io. Fortunately, there is a direct observation of the plasma parameters in the vicinity of Io obtained by the Galileo spacecraft at a closest approach of about $0.5 R_{Io}$ (900 km) [Frank et al., 1996]. It was observed that the plasma pressure increases by a factor of $\sim 2 - 3$. Then the spacecraft crossed the cold ionosphere of Io and no data are available. However, extrapolating the increasing curve reveals that the real enhancement of the gas pressure must be even bigger $\sim 4 - 6$. Besides this direct observation, computer simulations of the interaction between Io and its torus including mass loading effects have shown that the maximum of the pressure perturbations can exceed the background level by a factor of 4 [Combi et al., 1998].

The peculiarity of the above introduced explosion is related to two important facts: First, the slow mode waves are guided along the magnetic field (1D explosion), and second, the slow waves propagate inside a dipole flux tube with progressively decreasing cross section. For the Io flux tube ($L \sim 6$) the cross section of the tube decreases in 380 times within a distance of $\sim 7.13 R_J$, and in addition, the magnetic pressure increases by $\sim 1.5 \cdot 10^5$ times. As a result, the flow velocity has to increase towards Jupiter rather than to decrease as it used to happen after an usual explosion.

So, a scenario which will be justified in this paper can be described as follows (see Figure 1). A pressure pulse produced near Io generates two slow waves propagating along the Io flux tube to the southern and northern ionosphere of Jupiter. These slow waves turn out to be quickly converted into nonlinear waves due to a steepening mechanism. The flow velocity increases in the course of the shock propagation towards Jupiter, and can reach values of the order of the initial Alfvénic velocity (~ 150 km/s) at the Io orbit.

2 Basic equations

The geometrical situation of the problem is illustrated in Figure 1. To describe the perturbations of the magnetic field and the plasma parameters, we apply the system of ideal MHD equations without dissipation. As a next step, we consider a thin magnetic flux tube related to Io which has a relatively small radius compared with the total length of the tube. The specific situation in the Io torus reveals that we have to deal with a low plasma beta.

The MHD equation for the field aligned velocity component is

$$\rho \frac{\partial V}{\partial t} + \rho V \frac{\partial V}{\partial S} + \frac{\partial P}{\partial S} = \rho \frac{\partial}{\partial s} \left(\frac{GMm}{r} + 0.5m\Omega^2 y^2 \right), \quad (1)$$

where ρ , V , and P corresponds to the mass density, bulk velocity, and plasma pressure, respectively. Quantity G is the gravitational constant, M is the mass of Jupiter, r is the radial distance from the center of Jupiter, y is the distance to the rotational axis, k is the Boltzmann constant, T is the temperature assumed to be constant along the tube, and Ω is the angular speed of Jupiter. We note that the cross section of a thin magnetic flux

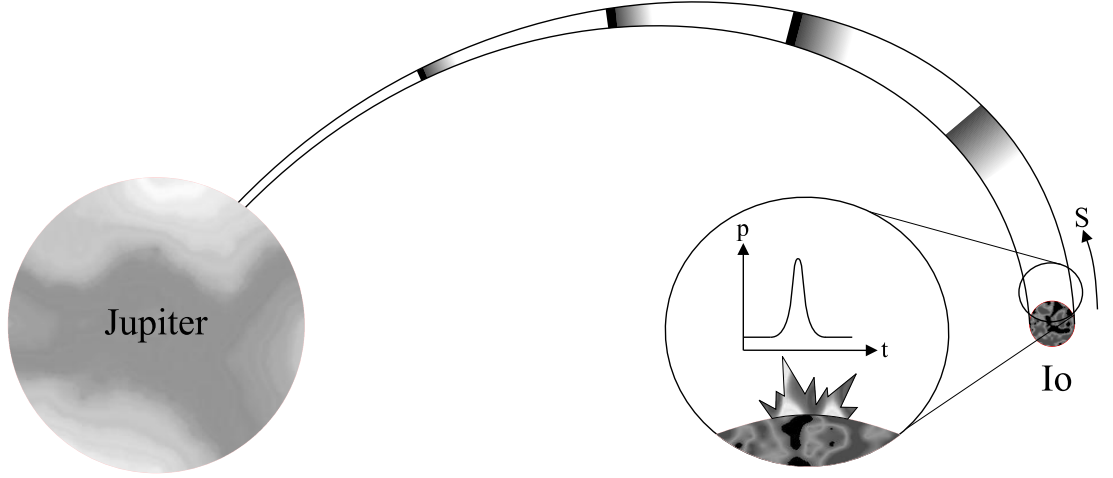


Figure 1: Schematic illustration of the development of a nonlinear slow mode wave and a field aligned electric field due to a pressure pulse near Io. The parameter S is introduced as the distance measured along the flux tube.

tube is $\propto 1/B$. Thus, assuming plasma motion along the magnetic field the conservation of mass leads to

$$\frac{\partial}{\partial t}\left(\frac{\rho}{B}\right) + \frac{\partial}{\partial s}\left(\frac{\rho V}{B}\right) = 0. \quad (2)$$

This system of equations (1, 2) is closed by the adiabatic equation

$$\frac{\partial}{\partial t}(P/\rho^\kappa) + V \frac{\partial}{\partial s}(P/\rho^\kappa) = 0. \quad (3)$$

As a next step, we normalize the magnetic field and the respective plasma parameters as follows $\tilde{\mathbf{R}} = \mathbf{R}/R_J$, $\tilde{t} = tV_{A0}/R_J$, $\tilde{P} = P/(m_i N_i V_{A0}^2)$, $\tilde{\rho} = \rho/(m_i N_i)$, $\tilde{\mathbf{B}} = \mathbf{B}/B_0$, $\tilde{\mathbf{V}} = \mathbf{V}/V_{A0}$, where R_J is the Jupiter radius, subscript 0 denotes the initial background parameters corresponding to the Io orbit, V_{A0} is the Alfvén velocity, m_i is the average ion mass, N_i is the ion density, and B_0 is the magnetic field induction. For our calculations, the initial background parameters are similar to those of Neubauer [1998] and Combi et al. [1998]

$$m_i \sim 20 \text{ amu}, \quad N_i = 3600 \text{ cm}^{-3}, \quad T_i = 100 \text{ eV}, \quad B_0 = 1835 \text{ nT}.$$

These parameters correspond to an Alfvén speed of $V_{A0} = 150 \text{ km/s}$ and a plasma beta of $\beta_0 = 0.04$. The undisturbed plasma parameters along the magnetic flux tube are assumed to satisfy the equilibrium equation

$$\frac{\partial p}{\partial s} = \frac{p}{kT} \frac{\partial}{\partial s} \left(\frac{GMm}{r} + 0.5m\Omega^2 y^2 \right). \quad (4)$$

Since we consider plasma motion along the magnetic field, we introduce the material coordinate α , which is proportional to the mass of the plasma in the magnetic tube of the length S

$$\alpha = \int_0^S (\rho/B) dS'. \quad (5)$$

Using the independent coordinate α instead of S , allows to rewrite the MHD system of equations in the normalized units as follows

$$\rho \frac{\partial V}{\partial t} + \frac{1}{B} \frac{\partial P}{\partial \alpha} = 0, \quad \frac{\partial}{\partial t} \left(\frac{B}{\rho} \right) - \frac{\partial V}{\partial \alpha} = 0, \quad (6)$$

$$P + B^2/2 = \Pi, \quad \frac{\partial S}{\partial t} = V, \quad \frac{\partial}{\partial t} \left(\frac{P}{\rho^\kappa} \right) = 0. \quad (7)$$

Here Π denotes the total pressure, i.e., $\Pi = P + B^2/2$, and κ is the adiabatic exponent.

3 Results of MHD simulations

Figure 2 shows the first stage of the slow-mode generation. The initial pressure pulse decays into two nonlinear slow waves propagating along the Io flux tube in opposite directions. The amplitudes of these waves are decreasing in the course of time, the leading fronts are getting more and more steep, and eventually the slow waves are converted into shocks. The distributions of the normalized velocity and plasma pressure are shown for different times in units R_J/V_{A0} . This initial stage is very similar to a classical 1D explosion, and the behaviour of all parameters (pressure and velocity) is also quite analogous. Thus, if the tube cross section would not change any more, the process of the wave propagation could be easily predicted: Slow shocks would travel along the flux tube, thereby gradually damped with decreasing flow velocity behind the shock fronts.

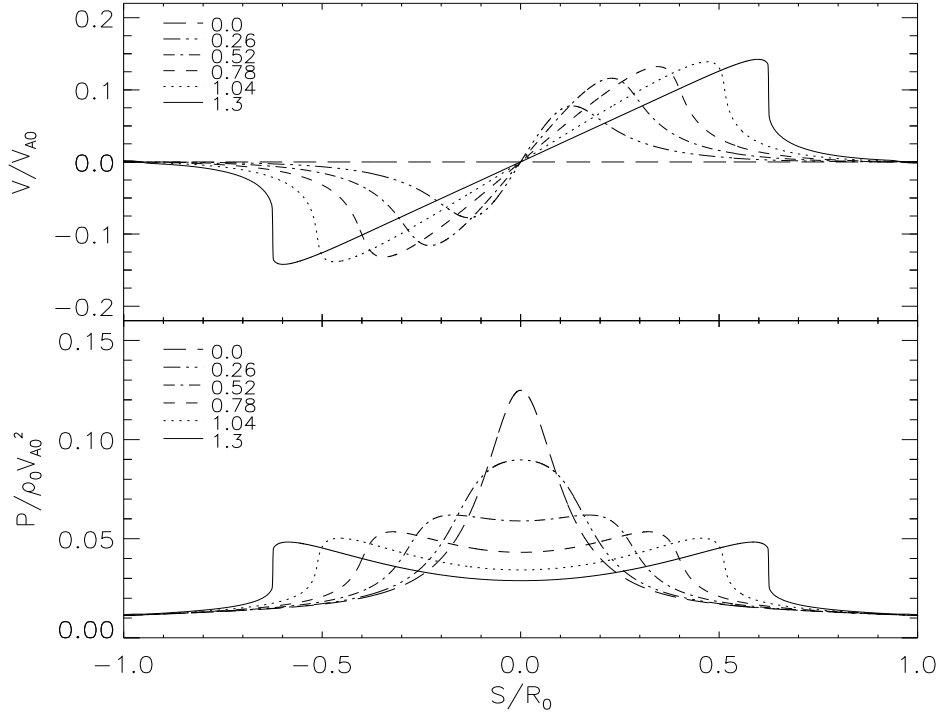


Figure 2: The first stage of the slow mode generation. The distributions of the normalized velocity and the plasma pressure are shown for different times in units R_J/V_{A0} .

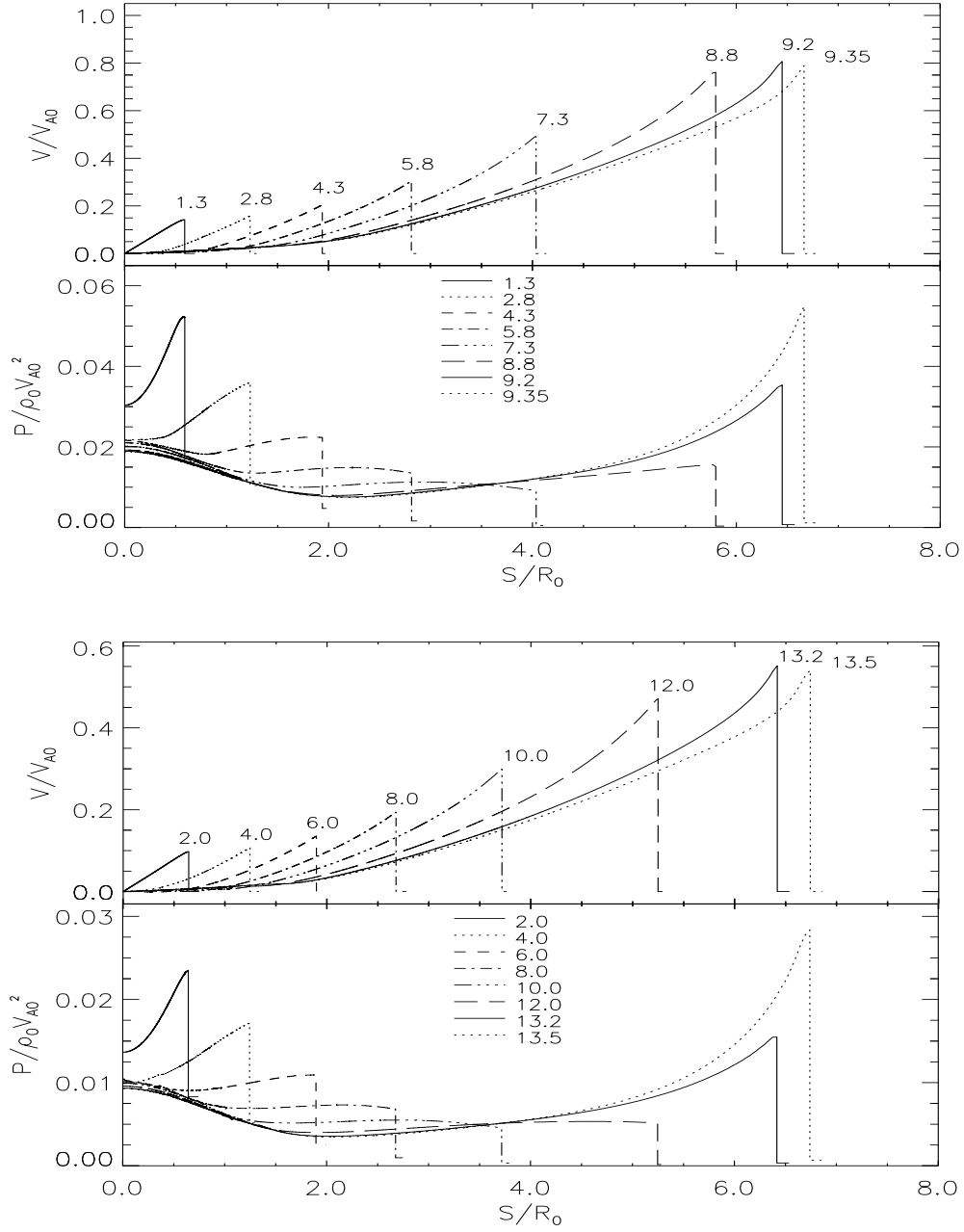


Figure 3: Propagation of the slow shock along the Io flux tube. The distributions of the plasma velocity and the plasma pressure are shown for two different initial values of the plasma beta as functions of the distance along the tube for different times in units R_J/V_{A0} .

However, the flux tube cross section is inverse proportional to the magnetic field strength and therefore, it has to decrease as r^3 due to the dipole field configuration. Hence, the plasma flow has to move into a more and more narrow flux tube.

Figure 3 shows the distributions of the velocity and plasma pressure as functions of the distance along the magnetic flux tube for the different shock positions corresponding to the different times scaled to R_J/V_{A0} and for two different values of the plasma beta, i.e., $\beta_0 = 0.02, 0.04$. One can see from Figure 3 that the wave amplitude (plasma velocity

behind the shock) firstly stays roughly constant as far as damping due to the expansion is balanced by the tube narrowing effect. After that, the tube cross section starts to decrease so rapidly that the wave amplitude begins to enhance. By the arrival at the point ($S \sim 6.3 R_J$), the plasma velocity reaches its maximum value $\sim 0.9 V_{A0}$. After this maximum point, the velocity starts to decrease near Jupiter because of the enhancement of the background pressure due to the gravitational force.

4 Conclusions

As it was shown, the explosion in a flux tube with an increasing magnetic field and correspondingly decreasing of the tube cross section is considerably different from an usual 1D explosion. The narrow channel effect leads to an intensification of the propagating wave rather than to damping due to its expansion. This effect might be important not only in the case of Io, but also for all other situations on the Sun or on other planets where pressure pulses can be produced inside a thin flux tube.

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