Interstellar magnetic field effects on the heliosphere

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Abstract. This paper summarizes the numerical results obtained by three-dimensional MHD simulations of the interaction between the solar wind and interstellar medium in Ratkiewicz and Ben-Jaffel [2002], Ratkiewicz and McKenzie [2002], and Ratkiewicz and Webb [2002]. We analyze the configuration in which Maxwell stresses lead to squeezing and/or pushing the heliospheric boundary. In particular, we explain the mechanism giving rise to a suction effect of the heliopause. Numerical results for the case of aligned interstellar MHD flow are compared with previous studies.

INTRODUCTION

The interaction between the solar wind (SW) and the interstellar gas (LISM) leads to the formation of the termination shock (TS) in the solar wind, the heliopause (HP) - the interface separating both media - and a bow shock (BS) in the interstellar plasma if the inflow is “supersonic”. This complex interaction involves stationary or time-dependent plasma-plasma interactions, magnetic field stresses, effects of neutrals, creation of pick-up ions and their acceleration at shocks (in particular, at the termination shock, where they give rise to anomalous cosmic rays (ACRs)), energetic neutral atoms (ENA), modification of the supersonic solar wind by ACRs and galactic cosmic rays (GCRs), and the modulation of the structure of the termination shock. A thorough review of the subject has been given by Zank [1999]; and the reader is also referred to papers by Ben-Jaffel et al. [2000], Fahr [2000], Izmodenov [2000], Ratkiewicz et al. [2000], Fichtner [2001], and references therein.

A theoretical model taking into account all these factors in a self-consistent way does not yet exist. The most complete studies so far have been given by Fahr et al. [2000]; a 5-fluid hydrodynamic model of the interaction between the solar wind and interstellar medium includes protons, hydrogen atoms, pick-up ions, galactic and anomalous cosmic rays, which does not however include the effects of the interplanetary and interstellar magnetic fields. Magnetic field effects have been studied in pure MHD models or MHD models including the effect of neutrals [Fujimoto and Matsuda, 1991; Baranov and Zaitsev, 1995; Washimi and Tanaka, 1996; Linde et al., 1998; McNutt et al., 1998, 1999; Pogorelov and Matsuda, 1998, 2000; Ratkiewicz et al., 1998, 2000, 2002; Aleksashov et al., 2000; Ratkiewicz and Ben-Jaffel, 2002; Ratkiewicz and Webb, 2002; Ratkiewicz and McKenzie, 2002]. The results highlight the importance of magnetic field effects in causing asymmetries and distortions of the heliospheric boundary.

MAIN ASSUMPTIONS OF THE MODEL

The solar wind expands radially from the Sun and interacts with the uniformly flowing magnetized interstellar plasma and neutral hydrogen. In the zeroth order approximation we may neglect the change in the distribution of the neutral hydrogen, resulting from the interaction, and assume a constant flux of neutral hydrogen through out. The interaction with neutral hydrogen occurs due to charge exchange between protons and H atoms both inside and outside the termination shock. The charge exchange cross-section σ is taken to be 2 × 10^{-15} cm^2. All other processes such as creation of pick-up ions and their acceleration at shocks, modification of the supersonic solar wind by ACRs and galactic cosmic rays (GCRs), the interplanetary magnetic field, heliolatitudinal dependence of solar wind are neglected.

Following, for example, Ratkiewicz and Ben-Jaffel [2002], we use the same set of MHD equations with a source term S on the RHS describing charge exchange with the constant flux of hydrogen:

\[
\frac{\partial \mathbf{U}}{\partial t} + \nabla \cdot \mathbf{F} = \mathbf{Q} + \mathbf{S}
\]
where \( \mathbf{U}, \mathbf{Q}, \) and \( \mathbf{S} \) are column vectors, and \( \mathbf{F} \) is a flux tensor defined as:

\[
\mathbf{F} = \begin{pmatrix}
\rho \\
\rho \mathbf{u} \\
\mathbf{B} \\
\rho E
\end{pmatrix}
\]

\[
\rho \mathbf{u} \mathbf{u} + I(p + \frac{\mathbf{B} \cdot \mathbf{B}}{8\pi \rho})\mathbf{u} \mathbf{u} + I(p + \frac{\mathbf{B} \cdot \mathbf{B}}{8\pi \rho}) - \frac{\mathbf{B} \cdot \mathbf{B}}{4\pi \rho} \\
\rho H \mathbf{u} - (\mathbf{u} \cdot \mathbf{B})
\]

\[
\mathbf{Q} = -\begin{pmatrix}
0 \\
\frac{\mathbf{B}}{4\pi} \\
\mathbf{u} \\
\mathbf{u} \cdot \mathbf{B}
\end{pmatrix}
\]

\[
\mathbf{S} = \rho \mathbf{v}_c \begin{pmatrix}
0 \\
\mathbf{V}_H - \mathbf{u} \\
\frac{1}{2}V_H^2 + \frac{3\gamma \mathbf{u}_H \cdot \mathbf{u}_H}{2\gamma - 1} - \frac{1}{2}u^2 - \frac{(\mathbf{u} \cdot \mathbf{B})^2}{(\mathbf{u} - \mathbf{B})^2}
\end{pmatrix}
\]

Here, \( \rho \) is the ion mass density, \( p = 2n_k T \) is the pressure, \( n \) is the ion number density, \( T \) and \( T_H \) (\( T_H = \text{const} \)) are ion and H atom temperatures, and \( \mathbf{u} \) and \( \mathbf{V}_H \) (\( \mathbf{V}_H = \text{const} \)) are the ion and H atom velocity vectors, respectively; \( \mathbf{B} \) is the magnetic field vector, \( E = \frac{1}{2}u^2 + \frac{\mathbf{u} \cdot \mathbf{u}}{2} + \frac{\mathbf{B} \cdot \mathbf{B}}{4\pi \rho} \) is the total energy, and \( H = \frac{\gamma}{\gamma - 1} p + \frac{u^2}{2} + \frac{\mathbf{B} \cdot \mathbf{B}}{4\pi \rho} \) is the total enthalpy per unit mass, \( \gamma \) is the ratio of specific heats. \( I \) is the 3 x 3 identity matrix. The charge exchange collision frequency is \( v_c = n_H \sigma u \), where \( n_H \) (\( n_H = \text{const} \)) is H atom number density, \( \sigma \) is the charge exchange cross-section, and \( u_* = (\mathbf{u} - \mathbf{V}_H)^2 + 128k_B(T + T_H)/(9\pi n_H) \) \( \sqrt{1/2} \) is the effective average relative speed of protons and H atoms, assuming a Maxwellian spread of velocities both for protons and H atoms. The flows are taken to be adiabatic with \( \gamma = 5/3 \). The additional constraint of a divergence-free magnetic field, \( \nabla \cdot \mathbf{B} = 0 \), in the numerical simulations is accomplished by adding the source term \( \mathbf{Q} \) to the RHS of (1), which is proportional to the divergence of the magnetic field. By adding \( \mathbf{Q} \) to the RHS of (1) assures that any numerically generated \( \nabla \cdot \mathbf{B} \neq 0 \) is advected with the flow, and allows one to limit the growth of \( \nabla \cdot \mathbf{B} \neq 0 \).

The coordinate system is Sun-centered, and the spherical \( (r, \theta, \psi) \) grid is chosen with a Cartesian correspondence of \( x = r \cos \theta \cos \psi, y = r \sin \theta \cos \psi, z = r \sin \theta \sin \psi \). The LISM velocity and magnetic field vectors define the x-y plane. The LISM velocity vector is in the positive x direction. The interstellar inclination angle \( \alpha \) is the angle between interstellar velocity \( \mathbf{V}_i \) and magnetic field \( \mathbf{B}_i \) vectors.

**GENERAL BEHAVIOUR OF THE HELIOSPHERIC BOUNDARY**

We have carried out a parametric study encompassing 90 cases of different boundary conditions of the interstellar medium in order to investigate how ionized and neutral interstellar hydrogen, and the interstellar magnetic field influence the interaction between the solar wind and LISM [Ratkiewicz and Ben-Jaffel, 2002]. For the solar wind we fix the boundary conditions. The inner boundary of the solar wind is taken at \( r_0 = 30 AU \), and corresponds to an unperturbed solar wind at \( 1AU \) with number density \( n_e = 8cm^{-3} \), velocity \( V_e = 400km^{-1} \), and Mach number \( M_e = 8 \). The unperturbed interstellar magnetized plasma is taken to have the same velocity (magnitude and direction) and temperature as neutral hydrogen.

At the outer boundary, located at \( 15000AU \), we take constant \( V_{is} = 26km^{-1} \) and \( T_{is} = 7000K \), and variable \( n_{is} = 0.034, 0.043, 0.061cm^{-3} \), \( B_{is} = 1.0, 1.4, 1.8, 2.2 \mu G \), \( \alpha = 30^\circ, 35^\circ, 40^\circ, 45^\circ, 50^\circ \), and \( n_H = 0.14, 0.24, 0.34cm^{-3} \) [Ben-Jaffel et al., 2000].

The heliospheric boundary structures reveal that the size of the heliosphere inside the termination shock decreases with an increase of the neutral hydrogen number density as well as with an increase of the ionized LISM component number density. However, the effect of the ions is much more pronounced.

The inflow of LISM neutral atoms into the heliosphere creates the pick-up ions by charge exchange with protons, and causes heating of the supersonic solar wind and cooling of the plasma beyond the termination shock. The intensity of the effective heating (by introducing a new separate hot ion component into the solar wind) and cooling demonstrates the key role played by neutral hydrogen in heating or cooling the plasma of the solar wind. Simultaneously very weak changes in temperature are observed with variations of interstellar plasma density.

The solar wind Mach number inside the termination shock decreases due to the interaction with the neutral hydrogen, while no changes are observed with variations of interstellar plasma density. Our results also show that the solar wind is decelerated by neutral hydrogen. (However, since filtration, which also slows the neutrals, is not taken into account, this introduces some errors in the deceleration of the solar wind).

For the assumed boundary conditions, the TS is located between \( 100 AU \) and \( 140 AU \) from the Sun; the HP is located between \( 170 AU \) and \( 220 AU \), respectively. As concerns a BS its strength and location depend strongly on the interstellar magnetic field inclination angle and intensity.

The results show that the main features of asymmetries do not depend on the hydrogen number density (except for a shift of the whole structure toward the Sun).
FIELD-ALIGNED MHD FLOW

In this section we examine numerical results for the case of aligned interstellar MHD flow with fixed boundary conditions for the solar wind and the interstellar plasma in which the magnetic field strength is varied between 1.0 to 3.0µG [Ratkiewicz and McKenzie, 2002]. The inner boundary conditions of the solar wind are the same as in previous section. At the outer boundary (at 15000 AU), we take $V_{\text{is}} = 26\text{km s}^{-1}$, and $T_{\text{is}} = 7000^\circ\text{K}$, $n_{\text{is}} = 0.07\text{cm}^{-3}$, $n_H = 0.24\text{cm}^{-3}$. The interstellar magnetic field $\vec{B}_{\text{is}}$, taken to be parallel to the velocity vector $\vec{V}_{\text{is}}$, varies in intensity in steps of 0.4µG.

The location of the heliopause as displayed by thermal pressure isobars shows up more clearly for larger magnetic field strength.

The changes in the bow shock shape and its location, can be grouped into four classes:
1. $B_{\text{is}} = 1.0$ and $1.4\mu G$, II. $B_{\text{is}} = 1.8$, III. $B_{\text{is}} = 2.2$, and IV. $B_{\text{is}} = 2.6$ and $3.0\mu G$.

For $V_A < c$ the shocks are fast and evolutionary [Landau, Lifshitz and Pitaevskii, 1984] (class I).
For $V_A > c$ there are three types of shocks, for super-Alfvénic flows [Landau, Lifshitz and Pitaevskii, 1984]:
1) the flow speed ahead, $u_{n1} > \sqrt{4V_A^2 - 3c_1^2}$. The shocks are fast and evolutionary (class II).
2) the flow speed ahead appears in the non-evolutionary range $V_A < u_{n1} < \sqrt{4V_A^2 - 3c_1^2}$, with $\vec{B}_{11} = \vec{B}_{12} = 0$, (class III).
3) the flow speed ahead appears in the non-evolutionary range, but $\vec{B}_{11} = 0, \vec{B}_{12} \neq 0$. Then a switch-on shock occurs ($M_{A1}$ lies in the range $1 \leq M_{A1} \leq 2\sqrt{1 - 3c_1^2/4V_A^2}$) (class IV).

If the BS becomes a switch-on shock the flow behind splits, and the stagnation line is evacuated. The heliopause is therefore sucked out towards the bow shock. As shown by Ratkiewicz et al. [2000] in the case of a parallel interstellar magnetic field, the magnetic pressure goes to zero in the vicinity of the stagnation point. On the other hand, the combined magnetic tension and total pressure forces attain their maximum values near the flanks of the heliopause. Therefore, under the influence of compressive magnetic forces the heliopause is squeezed out. This is due to the Lorentz force $\vec{J} \times \vec{B}$, which compresses the plasma on the flanks of the heliopause, and pushes the plasma in the anti-sunward direction just upstream of the stagnation point, where $\vec{B} \simeq 0$. A “tooth-paste tube” or a “suction” effect appears [Ratkiewicz and Webb, 2002]. This effect is a feature of all possible aligned MHD flows with sufficiently high magnetic field regardless of whether the flows are in the hyperbolic or elliptic regimes [Jeffrey and Taniuti, 1964].

Recently De Sterck and Poedts [2001] have studied the disintegration and reformation of intermediate shock segments in 3D MHD bow shock flows. They note that intermediate shocks can be stable when dissipation is properly taken into account for a wide range of dissipation coefficients. However, the exact conditions for shock stability depends on the magnitude and type of the perturbations and the magnitude of the dissipation coefficients. In fact both dispersion and dissipation play an important role in the stability of the shock. The switch-on interstellar bow shock here is an intermediate shock which can be stabilized due to the dissipation provided by the interaction of the plasma with the interstellar neutrals.
COMPARISON WITH PREVIOUS RESULTS

In this section we discuss results obtained by our model [Ratkiewicz and Webb, 2002] in the context of these obtained by Aleksashov et al. [2000]. We consider the interaction of the solar wind with the interstellar MHD flow for the unperturbed SW and LISM exactly the same parameters as Aleksashov et al. [2000]. For the solar wind at 1AU the number density is \( n_E = 7 \text{cm}^{-3} \), the velocity is \( V_E = 450 \text{km s}^{-1} \), and the sonic Mach number is \( M_E = 10 \) (the corresponding values at the inner computational boundary at 30 AU are then determined from the standard spherically-symmetric solar wind model). For the unperturbed interstellar magnetized plasma at the outer boundary (15000 AU) the velocity is taken \( V_{i_A} = 25 \text{km s}^{-1} \), the Mach number \( M_{i_A} = 2 \) (with the sound speed \( c = 12.5 \text{km s}^{-1} \)), the interstellar ionized hydrogen number density \( n_{iH} = 0.07 \text{cm}^{-3} \). We consider two cases in which the interstellar neutral hydrogen number density \( n_{iH} = 0.0 \) and \( 0.2 \text{cm}^{-3} \). The interstellar magnetic field \( \vec{B}_{i_A} \) is parallel to the velocity vector \( \vec{V}_{i_A} \) and varies from \( B_{iA} = 0.0, 2.6, 3.5 \mu G \), which correspond to Alfvén Mach numbers of \( \infty, 1.18 \) and \( 0.9 \), respectively.

Our results show three different types of solutions.

1. For \( M_A = \infty, M_{iA} > M_{i_A}, V_A < c \), the shock is fast and evolutionary. The solution displays the pure gas shock limit behavior.

2. For \( M_A = 1.18, M_{iA} < M_{i_A}, V_A > c \), the fast flow ahead appears in the non-evolutionary range \( V_A < V_{i_A} < \sqrt{4V_A^2 - 3c^2} \), a switch-on shock occurs, i.e., \( \vec{B}_{i1} = 0 \), \( \vec{B}_{i2} \neq 0 \). The solution is typical for a switch-on shock with a suction effect acting on the heliopause manifesting itself in the decrease of the number density in front of the heliopause along the stagnation line [Webb et al., 1994]. The heliopause is therefore sucked out towards the bow shock.

3. For \( M_A = 0.9, M_{iA} < 1 \) and \( M_{iA} > 1 \), the unperturbed flow speed appears in the elliptic regime, therefore there is no shock [Jeffrey and Taniuti, 1964]. The solution shows how a large parallel interstellar magnetic field \( (B_{iA} = 3.5 \mu G) \) moves the heliopause outward.

The results are qualitatively similar to those of Aleksashov et al. [2000] for super-Alfvénic, supersonic, field-aligned interstellar flow. In this regime the steady MHD equations are hyperbolic. For example, the nose of the heliopause moves outward from the Sun and the nose of the bow shock moves inward as the interstellar magnetic field strength increases from \( B_{iA} = 0 \mu G \) to \( B_{iA} = 2.6 \mu G \) (i.e., the Alfvén Mach number decreases from \( M_{iA} = \infty \) to \( M_{iA} = 1.18 \), and the corresponding sonic Mach number \( M_{sA} = 2 \)). But still our calculations indicate the appearance of a switch-on shock at an interstellar magnetic field strength \( B_{iA} = 2.6 \mu G \).

The results are qualitatively different from Aleksashov et al. [2000] in the sub-Alfvénic \( (M_A = 0.9, B_{iA} = 3.5 \mu G) \) and supersonic \( (M_{iA} = 2) \) interstellar flow regime, where the steady MHD characteristic are complex (i.e. in the elliptic flow regime). There is no bow shock in our model, whereas there is a bow shock in the corresponding results of Aleksashov et al. [2000].

To understand the differences in the results obtained by Aleksashov et al. [2000] and those presented here, one must note the different treatment of the problem in both models. The model presented here includes the neutral hydrogen as a constant flux, while in Aleksashov et al. [2000], the interstellar magnetic field is taken into account within the framework of an MHD model with source terms in which the trajectories of the hydrogen atoms are calculated by the Monte Carlo method. In the Aleksashov et al. [2000] model, the mutual interactions between the neutral component and plasma are included. This may cause a decrease in the influence of the magnetic field on the heliospheric boundary region.

SUMMARY

The interaction of a spherically symmetric solar wind with the magnetized interstellar plasma in the presence of a constant neutral hydrogen flux leads to the following phenomena: the supersonic solar wind is heated by the inclusion of pickup ions created through charge exchange with hot neutrals; the supersonic solar wind is decelerated; the heating and deceleration imply that the sound speed increases, and the hydrodynamic Mach number decreases with increasing heliocentric distance; changes in the shape and size of the termination shock, and reduction of heliocentric distances to the boundaries (TS, HP, and BS); the main features of asymmetries introduced by the interstellar magnetic field are the same as in the case without neutrals. However, this analysis does not take into account the magnetic field of the solar wind. The reconnection between the interplanetary and interstellar magnetic fields at the heliopause will modify this picture.

For the case of field-aligned flow, depending on the interstellar magnetic field intensity \( B_{iA} \): (a) the shock could be fast and evolutionary, or (b) a switch-on shock, or (c) a bow shock does not exist. In cases (b) and (c) the Lorentz force on the plasma results in a plasma evacuation in front of the heliopause and the suction effect occurs. The characteristic features of the solutions for such a flow configuration depends on the interplay between two effects:

1. The suction which moves the heliopause and the bow shock outward for increasing \( B_{iA} \), and
II. interstellar neutrals which push these discontinuity surfaces (when they exist) inward as $n_H$ increasing.

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