

Chapter 3

The Heliosphere: MHD Simulations

3.1 Introduction

In this chapter, the 3D magneto-hydrodynamic (MHD) model of *Pen et al.* [2003] is adapted and applied to the heliospheric environment. The purpose of this is twofold: Firstly, the MHD results emphasize the relevant heliopheric features outlined in Chapter 2, and secondly, the generated heliospheric geometry and computed plasma flow field, which cannot be prescribed analytically, will be used in Chapter 8 as input to a newly developed hybrid particle transport model. It should be emphasized that the model is not constructed to rival the complex MHD models of e.g. *Pogorelov et al.* [2008] and *Opher et al.* [2009], but rather to serve essentially as an illustrative model that can reproduce the relevant heliospheric features, with the emphasis being on particle transport. For this purpose, a single-fluid MHD approach is followed, neglecting all plasma and neutral species [see e.g. *Fahr et al.*, 2000], except protons and electrons. Because MHD studies are not the main topic of this thesis, only the most relevant background and results are given and discussed.

3.2 The Set of MHD Equations

MHD studies commonly refer to the treatment of a plasma as a magnetized fluid, obeying a set of governing equations, given as [e.g. *Landau and Lifshitz*, 1984]

$$\begin{aligned}\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{u}) &= 0 \\ \frac{\partial (\rho \vec{u})}{\partial t} + \nabla \cdot \left(\rho \vec{u} \otimes \vec{u} + p^* \mathbf{I} - \frac{1}{4\pi} \vec{B} \otimes \vec{B} \right) &= 0 \\ \frac{\partial e}{\partial t} + \nabla \cdot \left[(e + p^*) \vec{u} - \frac{1}{4\pi} \vec{B} (\vec{B} \cdot \vec{u}) \right] &= 0 \\ \frac{\partial \vec{B}}{\partial t} - \nabla \times (\vec{u} \times \vec{B}) &= 0.\end{aligned}\tag{3.1}$$

The first three equations describe the conservation of mass ρ , momentum $\rho\vec{u}$, and energy densities e , while the last is a restatement of Faraday's induction law for the frozen-in magnetic field $\vec{B}$. Here, external forces are neglected, as well as plasma sources and/or sinks. Further assumptions include vanishing conductivity, no viscous forces and no electrical resistivity (infinite conductivity). For a detailed derivation of these equations, see e.g. *Choudhuri [1998]*. It should be noted that the condition $\nabla \cdot \vec{B} = 0$ is used explicitly in the derivation of Eqs. 3.1, so that it is essential to fulfil the divergence free condition of $\vec{B}$ in the numerical model. Here, $\mathbf{I}$ symbolizes the identity matrix while $\otimes$ represents the outer (Dyadic) vector product. For shorter notation, the thermal and magnetic pressures are combined via $p^* = p + B^2/8\pi$. By setting $\vec{B} = 0$ in Eqs. 3.1, the MHD description reduces to the simpler set of hydrodynamic (HD) equations.

Eqs. 3.1 contain nine variables ($\rho, u_x, u_y, u_z, e, B_x, B_y, B_z, p$) and eight equations, so that a *closure equation* is needed to solve this set of equations self-consistently. This is obtained by using the ideal gas law, relating the thermal pressure to the temperature T through $p = nkT$ (with n the number density), so that the thermal energy becomes $p/(\Gamma - 1)$ with Γ the ratio of specific heats. The total energy therefore becomes

$$e = \frac{\rho|\vec{u}|^2}{2} + \frac{p}{\Gamma - 1} + \frac{B^2}{8\pi}. \quad (3.2)$$

The solar wind is a quasi-neutral plasma, and although the momentum of electrons can be neglected due to their small mass relative to that of protons ($m_e \ll m_p$), electrons may contribute significantly to the plasma's thermal properties. The closure equation used here includes this effect by assuming that both plasma species are in thermal equilibrium and modifies the ideal gas law to $p = 2nkT$ [e.g. *Pauls and Zank, 1997*], essentially doubling the thermal pressure and energy. Furthermore, $\Gamma = 5/3$ (protons being treated as a mono-atomic gas) and $\rho = nm_p$, so that Eqs. 3.1 essentially describes the interaction between solar and interstellar protons.

3.3 The MHD Solver

Eqs. 3.1 form a set of first-order partial differential equations (PDEs), which, under most physical conditions, must be solved numerically. In general this is done by first solving the fluid equations (the first three conservative equations) while keeping $\vec{B}$ constant, whereafter the induction equation is solved by keeping the fluid variables fixed. For this thesis, the 3D MHD solver of *Pen et al. [2003]* is used to solve Eqs. 3.1. This well documented numerical scheme uses the total variation diminishing scheme of *Jin and Xin [1995]* to advect the fluid variables, while the constrained transport (CT) approach of *Evans and Hawley [1988]* is used to update $\vec{B}$ and allows for the fulfilment of $\nabla \cdot \vec{B} = 0$. The present model solves Eqs. 3.1 on a 3D Cartesian grid, where the fluid variables are specified at the cell centres and $\vec{B}$ at the cell faces, a prerequisite for CT. For a detailed review on solving HD equations, see *Le Veque [2002]*, while *Tóth [2000]*

provides a detailed comparison between different MHD solvers. As most MHD schemes are explicit in time, the Courant-Friedrichs-Lewy (CFL) condition [Courant *et al.*, 1928] imposes a constraint on the numerical time step Δt ,

$$\Delta t = \varphi \cdot \frac{\Delta x}{\max \left\{ |\vec{u}|, V_S, V_A, \sqrt{V_S^2 + V_A^2} \right\}}, \quad (3.3)$$

with Δx the size of a numerical cell (held constant throughout), $V_S = \sqrt{\Gamma p / \rho}$ the local sound speed, $V_A = B / \sqrt{4\pi\rho}$ the local Alfvén speed (in CGS units) and $\varphi \in (0, 1)$ a constant. Typically, a value of $\varphi = 0.5$ is used, although the choice of φ is a contest between computational speed (a larger value of φ ; faster convergence), and numerical accuracy and dispersion (a smaller value of φ ; also enhancing numerical stability). The CFL condition forces the numerical scheme to update at a rate faster than the fastest rate at which information can travel in the system.

3.4 The Alfvén Wings Test

Although Pen *et al.* [2003] provides various tests and benchmarks for the MHD model, this section describes an additional test conducted to ascertain the validity of the MHD solver. Also, the so-called Alfvén wings test conducted here, is rooted in heliospheric space physics. Drell *et al.* [1965] showed that when a large obstacle is placed inside of a magnetized flow, standing MHD waves are generated in the $(\vec{u}, \vec{B})$ plane. This effect was shown to be present when artificial satellites were placed in Earth’s simulated magnetosphere [Kopp and Schröer, 1998], as well as during the interaction between Io and the Jovian magnetosphere [Neubauer, 1980]. In this work, the approach of Kleimann [2005] is closely followed.

An obstacle is placed at the origin of the MHD model’s computational region, plasma flow is assumed to be from the $-x$ direction, while $\vec{B} = B\mathbf{z}$, with the quantities $\rho = 1$, $|\vec{u}| = 1$, $|\vec{B}| = 1$ and $p = 0.5$. The generated waves, in this case Alfvén and magnetosonic waves, are therefore expected to be visible in the xz -plane, propagating, in the rest frame of the obstacle, along the characteristics,

$$\vec{V}_{\pm} = \begin{cases} \vec{u} \pm V_A \mathbf{e}_B & : \text{visible in the speed} \\ \vec{u} \pm V_S \mathbf{e}_B & : \text{visible in the pressure} \end{cases} \quad (3.4)$$

when examining the resulting speed or pressure respectively with $\mathbf{e}_B = \vec{B}/|\vec{B}|$ a unit vector directed along the magnetic field and valid for $V_S < V_A$.

Assuming Galilean speed transformations to the rest frame of the obstacle is appropriate, the resulting speeds at which the waves propagate are then

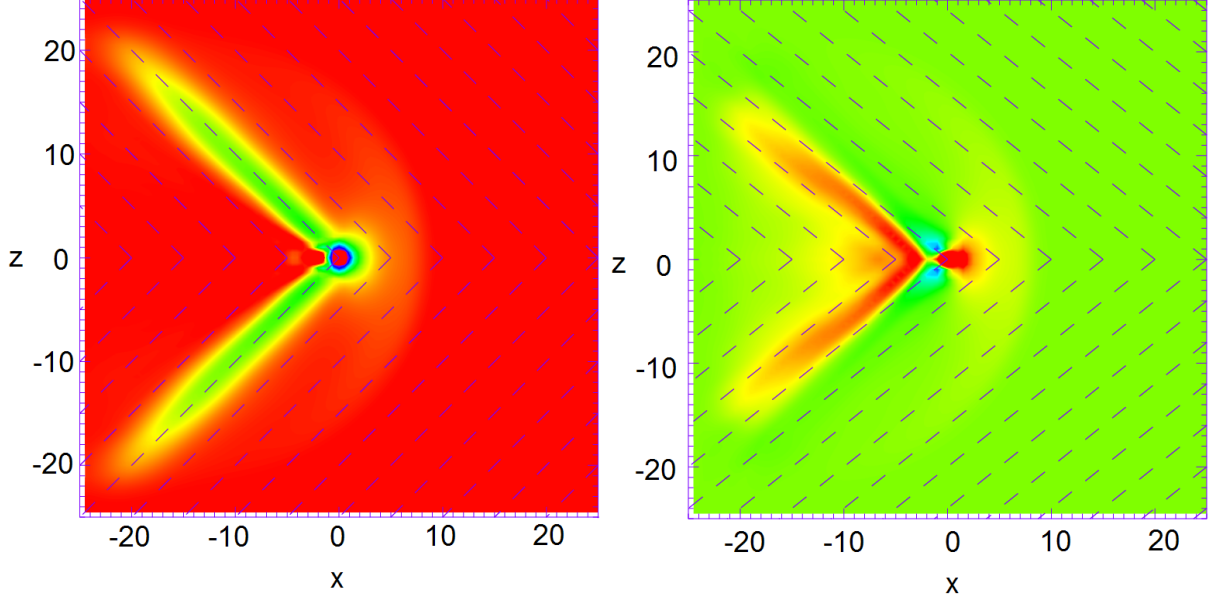


Figure 3.1: Results from the Alfvén wings test of the MHD model. The left panel shows $|\vec{u}|$ and the right p as a contour plot in the $(\vec{u}, \vec{B})$ plane. The dashed lines show the characteristic along which the generated MHD waves (Alfvén waves on the left and magnetosonic waves on the right panel) are expected to propagate, according to Eqs. 3.4 and 3.5.

$$|\vec{V}| = \begin{cases} \sqrt{|\vec{u}|^2 + V_A^2} & : \text{ visible in the speed} \\ \sqrt{|\vec{u}|^2 + V_S^2} & : \text{ visible in the pressure} \end{cases} \quad (3.5)$$

Results from the Alfvén wings test are shown in Fig. 3.1, where the speed (left panel) and pressure (right panel) are shown in terms of a contour plot in the xz -plane. The propagating waves are clearly visible as the propagating disturbances (Alfvén waves on the left and magnetosonic waves on the right), being generated at the origin, propagating away along $\pm z$ (i.e. along the unperturbed $\vec{B}$), while being convected towards the $-x$ direction. Also shown on the figure as the dashed lines are the expected characteristics along which the waves are expected to propagate using Eqs. 3.4 and 3.5. This test therefore confirms that the MHD model is capable of exciting the expected MHD waves, while also reproducing their expected speeds closely.

The modelled Alfvén wing is again shown in Fig. 3.2, now as the grey shaded surface (an iso-surface of $|\vec{u}|$). The blue line shows the orientation of $\vec{u}$, while the red that of $\vec{B}$. As expected, the MHD waves are limited to the xz -plane. The terminology of a modelled *wing* should now be apparent.

3.5 Boundary and Initial Conditions

For heliospheric purposes, the computational domain of the MHD model is a 3D cube with a volume of $(800 \text{ AU})^3$, centred on the Sun, subdivided into a grid containing $500 \times 500 \times 500$ cubical cells, each side with a length of 1.6 AU. Absorbing boundary conditions are imposed

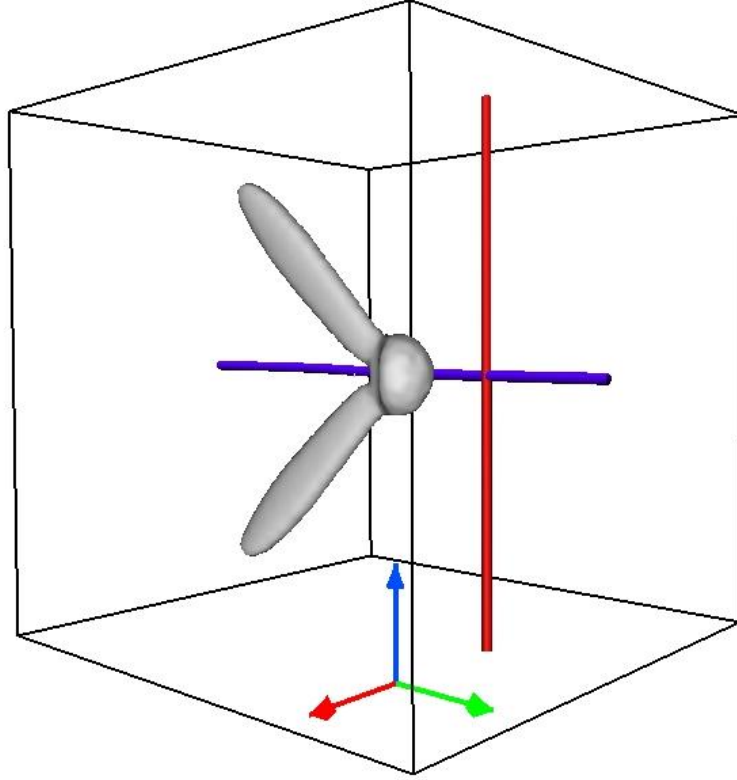


Figure 3.2: An illustration of the modelled Alfvén wing (the shaded surface) as an iso-surface of $|\vec{u}|$. The blue line shows the orientation of $\vec{u}$ and the red line that of $\vec{B}$. The arrows indicate the right-handed coordinate system used: Blue points along z , green along x and red along $-y$.

on all boundaries, except the $+y$ boundary, where the ISM is continually specified, forming an inflow boundary. The model is initiated by specifying a heliospheric boundary condition within a radius of $r = 50$ AU from the origin which is filled by solar material, while the rest of the computational volume is filled by the ISM.

Inside of the heliospheric boundary, a constant and radially outwards flowing solar wind is assumed with $|\vec{u}| = 400 \text{ km.s}^{-1}$. Adiabatic expansion [see e.g. *Snyman, 2007*] of the solar wind plasma is assumed, with $n \propto r^{-2}$ and $T \propto r^{-4/3}$, normalized to $n_0 = 5 \text{ particles.cm}^{-3}$ and $T_0 = 10^5 \text{ K}$ at $r_0 = 1 \text{ AU}$ (the position of Earth). An unmodified Parker HMF is assumed with a flat HCS, normalized to $B_0 = 5 \text{ nT}$, with the HMF ecliptic plane (here also the equatorial plane) lying in the xy -plane.

The ISM is initialized with the parameters $|\vec{u}| = 26 \text{ km.s}^{-1}$, $B_0 = 3 \mu\text{G}$, $T = 10^4 \text{ K}$ and $n = 0.2 \text{ particles.cm}^{-3}$. The value of n used here is a factor of ~ 2 larger than derived from observations. This is done to force the single fluid modelled heliosphere to the appropriate dimensions as observed and given by more complex multi-fluid MHD models [see also *Müller et al., 2008*]. Furthermore, $\vec{u}$ is directed along the $-y$ direction (so that the yz -plane corresponds to the meridional plane) and $\vec{B}$ inclined $\sim 45^\circ$ with respect to both the equatorial and meridional plane, i.e. $\vec{B} = B_0 (-0.4, -0.82, -0.4)$.

After initialization, the projection scheme of *Brackbill and Barnes* [1980] is applied to insure that the condition $\nabla \cdot \vec{B}$ is fulfilled. The system of equations is then iterated time dependently until sufficient convergence has been achieved, resulting in a steady-state solution.

3.6 A Modelled Heliosphere

Fig. 3.3 shows the computed heliospheric geometry obtained from the MHD model in terms of ρ (panel a), $|\vec{u}|$ (panel b), $|\vec{B}|$ (panel c) and T (panel d) in the meridional plane of the heliosphere. The assumed trajectories of the V1 and V2 spacecraft are projected onto the same plane. It should be kept in mind that these spacecraft are also separated by $\sim 50^\circ$ azimuthally. ISM flow is directed from the right, with a BS forming at ~ 200 AU from the Sun in the nose direction along the equatorial plane [see also *Pauls et al.*, 1995]. The BS is especially pronounced in terms of ρ and $|\vec{B}|$ as a large compression formed by the drop in $|\vec{u}|$. Recently, *McComas et al.* [2012], inferring from IBEX observations, have shown that the ISM flow may be slower, $\sim 23 \text{ km.s}^{-1}$, causing it to be initially subsonic and the BS to be replaced by a much more extended bow-wave region. Moreover, *Pogorelov et al.* [2009] have shown that even when the ISM is initially supersonic, the formation of the BS can be suppressed by increasing the magnetic pressure in the ISM. The absence of a BS, and the corresponding hydrogen built-up (referred to as the hydrogen wall), also represent challenges in explaining Ly- α observations and are currently being investigated in detail [*Zank et al.*, 2013].

Moving inwards from the BS along the stagnation line, the HP is present at ~ 100 AU, separating solar and interstellar material. The HP is most evident in the profiles of $|\vec{u}|$, where ISM flow decreases to almost zero at the HP close to the equatorial plane. ISM flow actually reaches zero at the so-called stagnation point. The region between the HP and the BS is generally referred to as the outer heliosheath. The term *outer heliosheath*, for the purposes of this work and especially Chapter 8, refers to the whole perturbed ISM region beyond the HP. This broader definition is also compatible with the absence of a BS. The fact that $\vec{u} \sim 0$ directly beyond the HP was expected to be the experimental signal of the crossing of the HP by V1. Using inferred plasma speed values, *Decker et al.* [2012] concluded that the flow speed at V1 is at present compatible with zero and that the spacecraft is very close to crossing the HP. However, *Pogorelov et al.* [2012] showed that these observations might be due to solar cycle related effects. It is generally believed that the HP crossing of V1 is imminent, or may have already happened [e.g. *Webber et al.*, 2012a], although no *in situ* plasma observations can confirm this at present.

At ~ 75 AU in the equatorial plane, the TS is encountered where the supersonic solar wind decreases to subsonic speeds. The existence of the TS was confirmed when V1 crossed into the inner heliosheath at a radial distance of ~ 94 AU in 2004 [*Stone et al.*, 2005] and V2 at ~ 84 AU in 2007 [*Stone et al.*, 2008]. The long awaited crossing of the TS led to a couple of surprises (from an MHD point of view), most notable that the TS is much weaker than anticipated with a compression ratio of ~ 2 , as compared to the maximum value of ~ 4 [*Richardson et al.*, 2008].

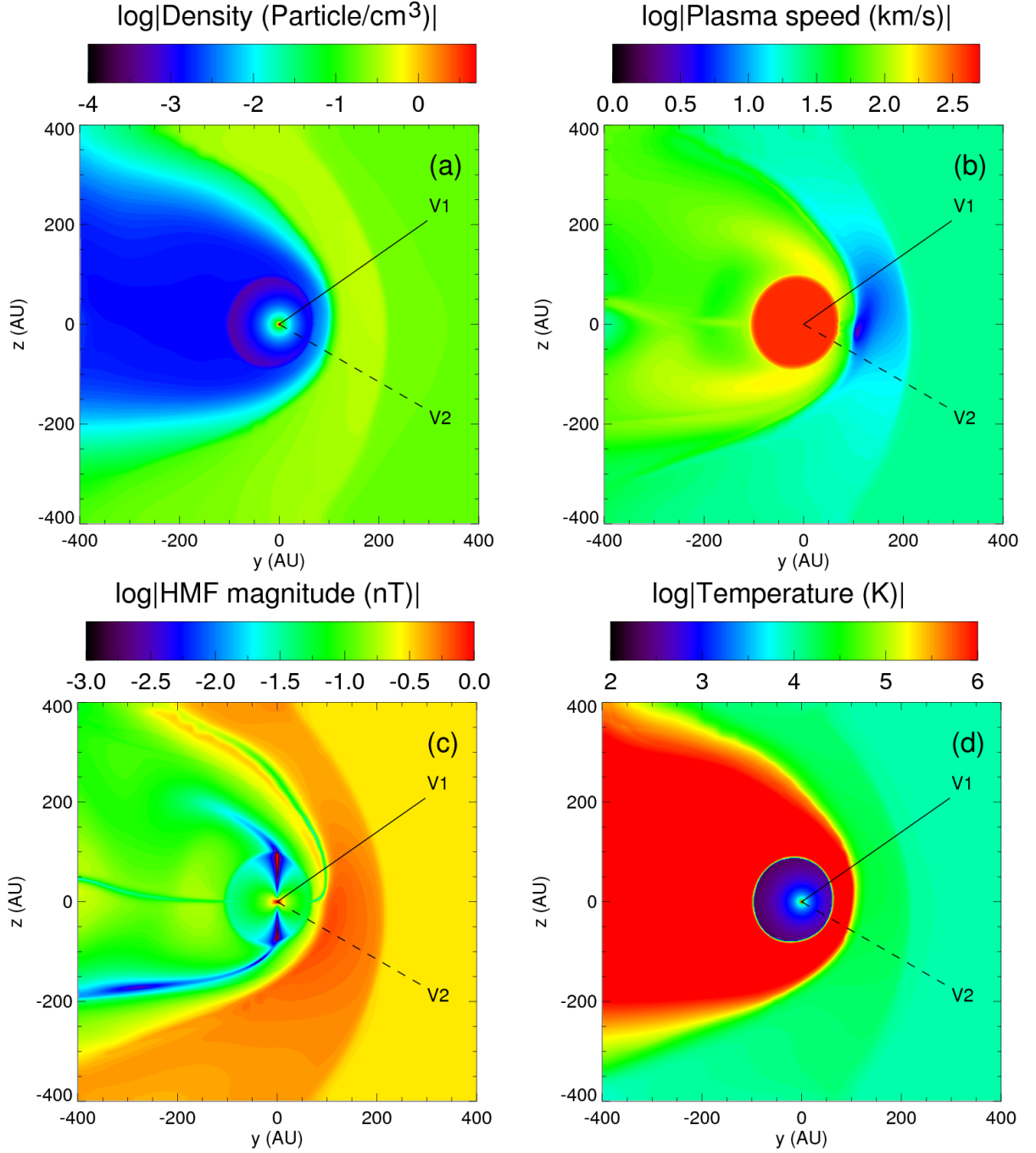


Figure 3.3: The modelled heliospheric environment in terms of ρ (panel a), $|\vec{u}|$ (panel b), $|\vec{B}|$ (panel c) and T (panel d) in the meridional plane of the heliosphere. Interstellar flow is directed towards the left, while the approximate trajectories of the V1 and V2 spacecraft (projected onto the same plane) are indicated by the solid and dashed lines, respectively.

It is also apparent that the bulk of the solar wind energy is dissipated into non-thermal ions [Decker *et al.*, 2012], rather than into the heating of the post-shock plasma. As this effect is not currently taken into account, panel (d) of Fig. 3.3 illustrates the *hot* inner heliosheath that was expected.

Most notably, the V1 and V2 crossings of the TS indicated that the heliosphere exhibits a north-

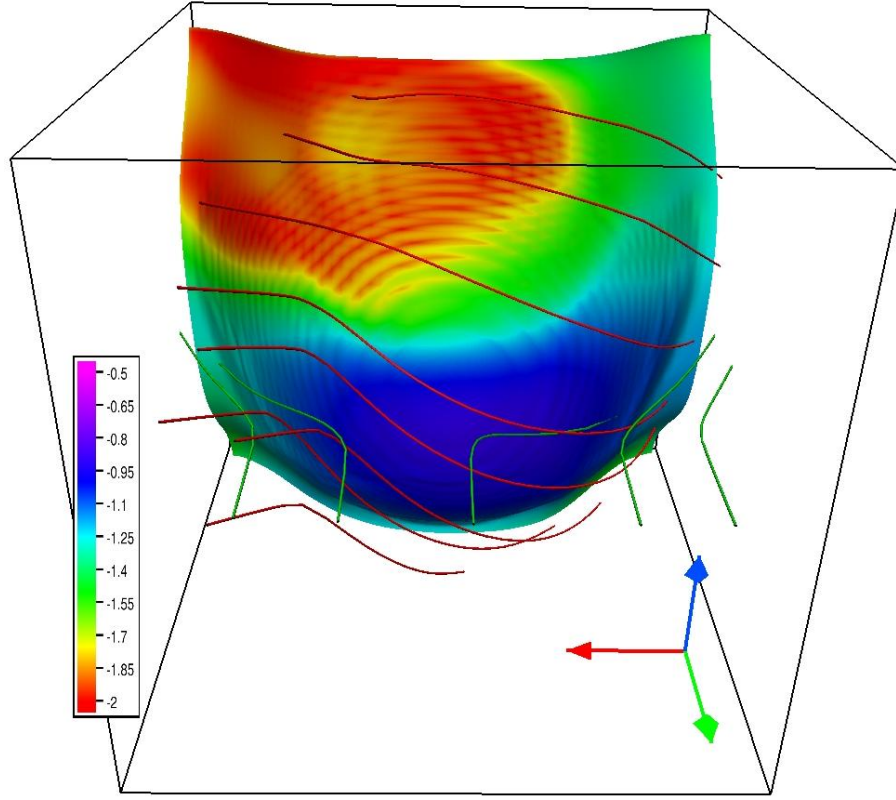


Figure 3.4: The modelled HP shown as a shaded surface and coloured according to the corresponding magnetic pressure (on an inverted colour scale where dark blue indicates a larger value). Examples of the modelled ISM $\vec{u}$ and $\vec{B}$ are indicated by the green and red lines respectively. The arrows indicate the right handed coordinate system used with green pointing along y , blue along z and red along x .

south geometrical asymmetry, with the heliosphere more compressed in the southern hemisphere. Modelling by *Opher et al.* [2006] showed that the orientation of the ISM $\vec{B}$ can be responsible for such an asymmetry; an effect also present in the results shown in Fig. 3.3. It can clearly be seen in panel (c) that the ISM $\vec{B}$ piles up in the southern hemisphere close to the HP, thus exerting more magnetic pressure on this region of the heliosphere, and essentially compressing the southern hemisphere [see also *Pogorelov et al.*, 2007]. The tail region of the heliosphere can also be seen to be deflected upwards. Results from the IBEX mission [*McComas et al.*, 2009], and subsequent modelling [e.g. *Pogorelov et al.*, 2011; *Heerikhuisen and Pogorelov*, 2011], collaborate such a choice of an inclined ISM $\vec{B}$. Also note that the HCS in the presented results flips towards the northern hemisphere, making this asymmetry even more pronounced. To further illustrate this asymmetry, Fig. 3.4 shows the modelled HP, as the shaded surface, along with the ISM $\vec{u}$ (green lines) and $\vec{B}$ (red lines). Note the draping of the magnetic field lines close to the HP. The HP is coloured according to the $\log_{10}$ of the magnetic pressure at its position (in arbitrary units on a linear and inverted colour scale) with a much larger pressure exerted on the southern heliospheric regions (the dark blue regions). As shown by *Pogorelov et al.* [2007], adopting an orientation of the ISM $\vec{B}$ as done here, results in a heliosphere without any plane of symmetry.

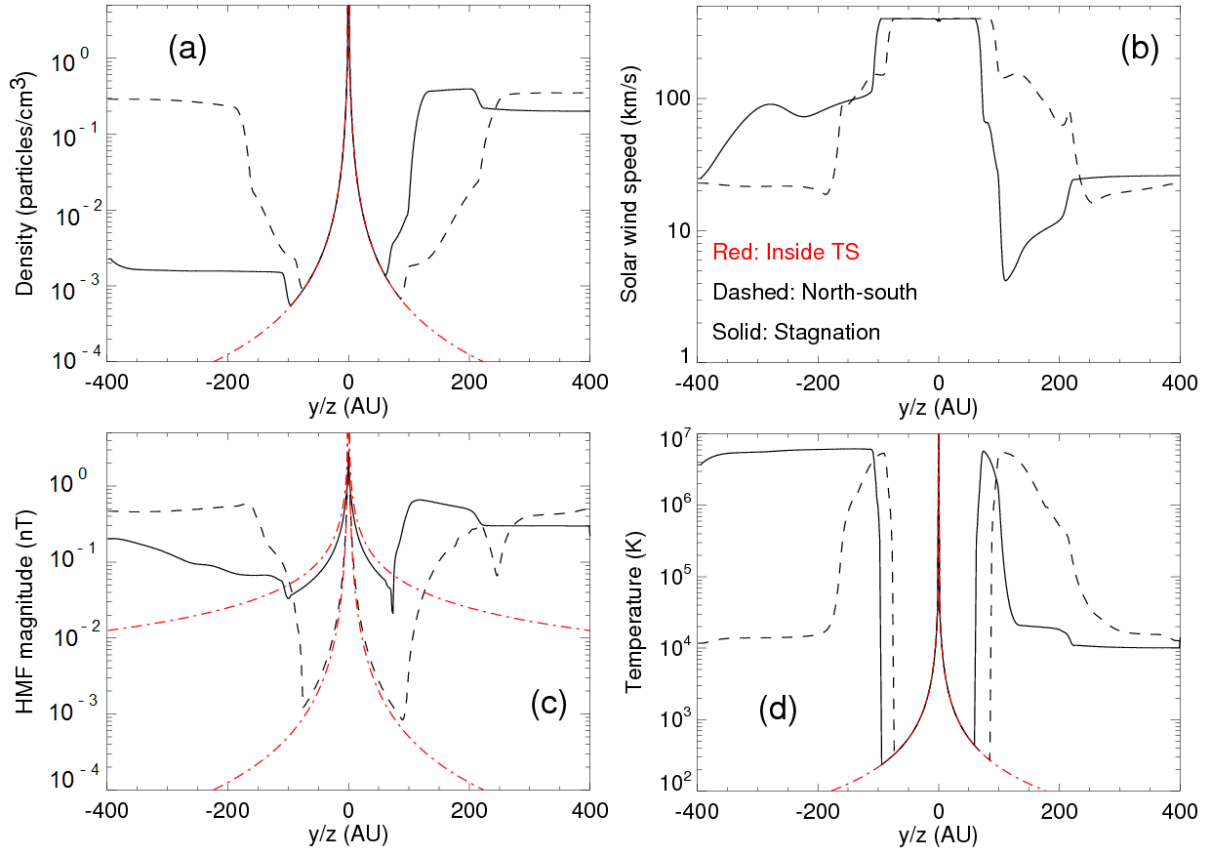


Figure 3.5: Similar to Fig. 3.3, except that the plasma properties are shown as cuts along the y -axis (solid line, referred to as the stagnation line) and the z -axis (dashed line, referred to as the north-south line). The red lines show the assumed profiles of these quantities in the inner heliospheric boundary, but extrapolated to the boundaries of the computational region. In Panel (c) two such lines are shown, which correspond to the different radial profiles of the HMF in the equatorial and polar regions.

Fig. 3.5 shows selected cuts through the MHD computational region. The solid line corresponds to a cut along the y -axis (referred to as the stagnation line) and the dashed line along the z -axis (referred to as the north-south cut). The red lines show the assumed profiles inside the inner heliospheric boundary condition, but are extended to the edges of the computational region in order to make deviations from these profiles clearer. The ρ profiles show the expected $\propto r^{-2}$ decrease inside the TS, whereafter it is compressed by a factor of ~ 4 at the TS. A second compression occurs at the BS (only present in the nose direction). This profile illustrates the geometrical asymmetry of the TS very clearly: In the nose direction, the TS is located at ~ 75 AU and at ~ 100 AU in the tail region – the well-known nose-tail asymmetry. In the southern hemisphere, the TS is located at ~ 75 AU and at ~ 100 AU in the northern hemisphere – corresponding to the north-south asymmetry discovered by the Voyager spacecraft. The profiles of $|\vec{u}|$ illustrate the same behaviour, although a compression of ρ generally corresponds to a drop in $|\vec{u}|$ (in order to conserve mass-flux) and a compression of $|\vec{B}|$. The HCS is also present in the results of panel (c): Note the decreases of $|\vec{B}|$ directly beyond the TS along the stagnation line and again at ~ 250 AU in the northern hemisphere. The profile of T illustrates the heating of the plasma at both the TS and the BS.

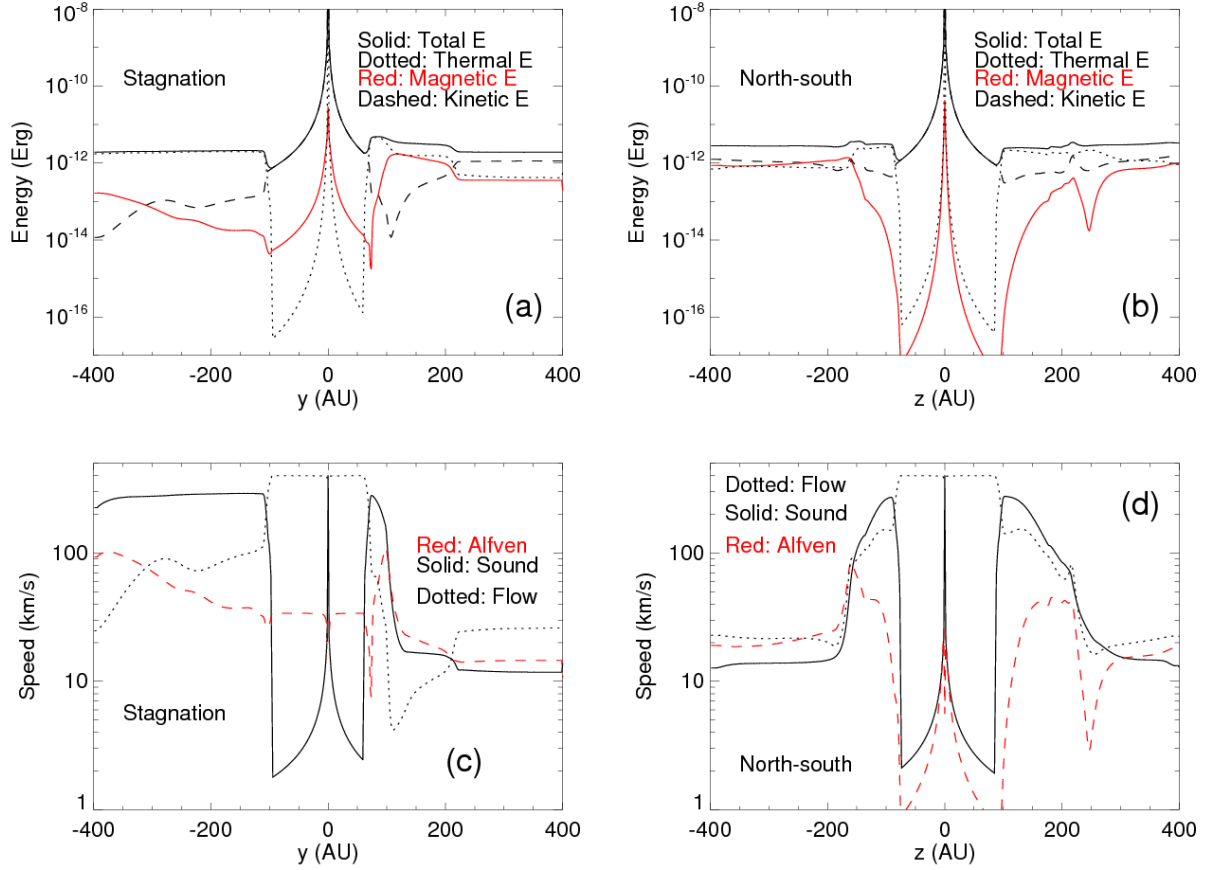


Figure 3.6: The top panels show the relative contribution of different mechanisms (solid line: total energy; dotted line: thermal energy; red solid line: magnetic energy; dashed line: kinetic energy) to the total plasma energy (the left panels show a cut along the y -axis and right panels along the z -axis). Note that $1 \text{ Erg} = 10^{-7} \text{ J}$. The bottom panels show the different plasma speeds (dotted line: $|\vec{u}|$; solid line: V_S ; red dashed line: V_A).

The behaviour of a plasma near a shock front can be described by the Rankine-Hugoniot shock relations [see e.g. *De Hoffmann and Teller, 1950; Jones and Ellison, 1991*]. Three scenarios are briefly presented here, namely: The shock relations for a purely HD shock, for a perpendicular MHD shock (where $\vec{B}$ is perpendicular to both $\vec{u}$ and the shock normal) and for a parallel MHD shock (with $\vec{B}$ parallel to both $\vec{u}$ and the shock normal). It should be noted that the formalism of both parallel and perpendicular shocks are spacial cases of oblique MHD shocks. In the equatorial regions, the TS can be approximated as a perpendicular shock, although it becomes increasingly parallel towards the polar regions. The status of the BS depends on the assumed orientation of $\vec{B}$ in the ISM. For the present results, the BS is a mixture of both types of MHD shocks.

When considering time independent 1D HD flow, Eqs. 3.1 reduce to

$$\begin{aligned}
\frac{\partial}{\partial x}(\rho u) &= 0 \\
\frac{\partial}{\partial x}(\rho u^2 + p) &= 0 \\
\frac{\partial}{\partial x}\left(\frac{1}{2}\rho u^3 + \frac{\Gamma}{\Gamma-1}up\right) &= 0,
\end{aligned} \tag{3.6}$$

which can be integrated across a shock front to reduce to

$$\begin{aligned}
s &= \frac{(\Gamma+1)M_1^2}{(\Gamma-1)M_1^2+2} \\
p_2 &= p_1 \frac{2\Gamma M_1^2 - (\Gamma-1)}{\Gamma+1},
\end{aligned} \tag{3.7}$$

where the subscripts 1 and 2 refer to plasma quantities directly in front and beyond the shock with $u_1 > u_2$. The Mach number is defined by $M = u/V_S$ and the compression ratio as $s = u_1/u_2 = \rho_2/\rho_1$. Three scenario, characterized by M_1 , are now possible: 1) When $M_1 = 1$, the flow is not initially supersonic and no shock forms, resulting in $s = 1$ and $p_2 = p_1$. 2) The scenario $M_1 < 1$ is not valid, as entropy is not conserved. 3) In the limit of $M_1 \rightarrow \infty$ (the case of a very strong shock), the compression ratio reaches its maximum value of $s \rightarrow 4$, although the pressure increase is unbounded, $p_2 \rightarrow \infty$. The MHD results in this section indicate a strong shock, with s close to its maximal value, as the effects of non-thermal particles are not included in the present model.

When $\vec{B}$ is included in the shock relations, two additional relations emerge

$$\begin{aligned}
B_{n1} &= B_{n2} \\
(\vec{u} \times \vec{B})_{t1} &= (\vec{u} \times \vec{B})_{t2},
\end{aligned} \tag{3.8}$$

where the subscripts n and t refer to vector components directed normally and tangentially to the shock front. For a parallel shock (where the tangential component of $\vec{B}$ vanishes), the magnetic field is not affected by the shock with $B_2 = B_1$, and, in general, parallel shocks can be treated as purely HD shocks. For a perpendicular shock, however, $B_2/B_1 \rightarrow 4$ when $M_1 \rightarrow \infty$, so that the magnetic field is compressed by the same ratio as ρ . Such a situation is observed in the presented MHD results at both the TS and the BS. Moreover, for a perpendicular shock, an additional condition is imposed on u_1 for the shock to form, namely that

$$u_1^2 > V_{S,1}^2 + V_{A,1}^2 \tag{3.9}$$

in line with the modelling results of *Pogorelov et al.* [2009] that show that the BS can, in principle, *disappear* when the ISM $\vec{B}$ is quasi-perpendicular, and the magnitude thereof is increased sufficiently.

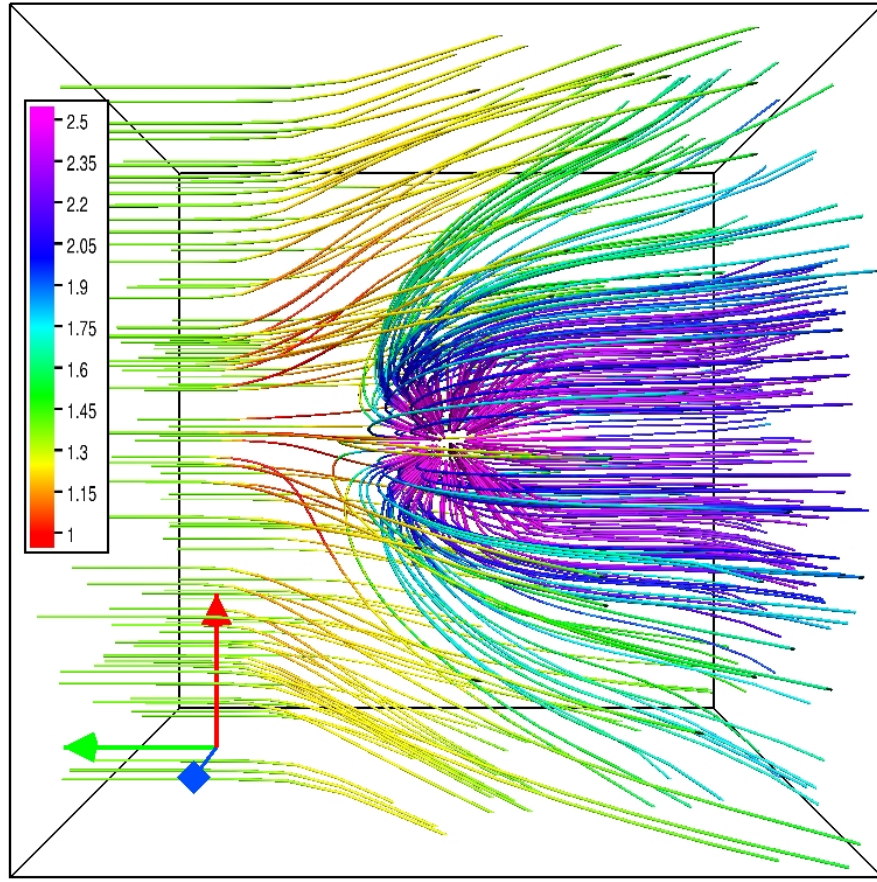


Figure 3.7: The resulting $\vec{u}$ as computed by the MHD model. The flow lines are coloured according to $|\vec{u}|$. Note that an inverted colour scale is used where red corresponds to smaller values of $|\vec{u}|$.

The top panels of Fig. 3.6 compare the relative contribution of different mechanisms to the total plasma energy. The left panels show a cut along the stagnation line and the right panels along the north-south line. Inside the TS, and beyond the HP, the kinetic energy contribution dominates, whereas the thermal energy dominates within the heliosheath. It is important to note that the magnetic energy contributes significantly near the heliopause so that $\vec{B}$ can play an important role in shaping the heliosphere.

In the bottom panels of the figure, $|\vec{u}|$, V_S and V_A are compared. Inside the TS, and beyond the BS, the flow is both supersonic and super-Alfvénic, so that, according to Eq. 3.9, a BS will form for any orientation of $\vec{B}$. As expected, the plasma flow is subsonic in both the inner and outer heliosheath regions.

Fig. 3.7 shows an illustration of the modelled $\vec{u}$ throughout the computational region. The flow lines are coloured according to the $\log_{10}$ of $|\vec{u}|$, with red indicating a slower speed. The flow lines clearly indicate the non-radial solar wind flow beyond the TS, where the solar wind develops strong azimuthal and polar components, before being deflected towards the heliospheric tail regions. Similarly, the ISM $\vec{u}$ is deflected along the HP. Note the small values of $|\vec{u}|$ near the stagnation point.

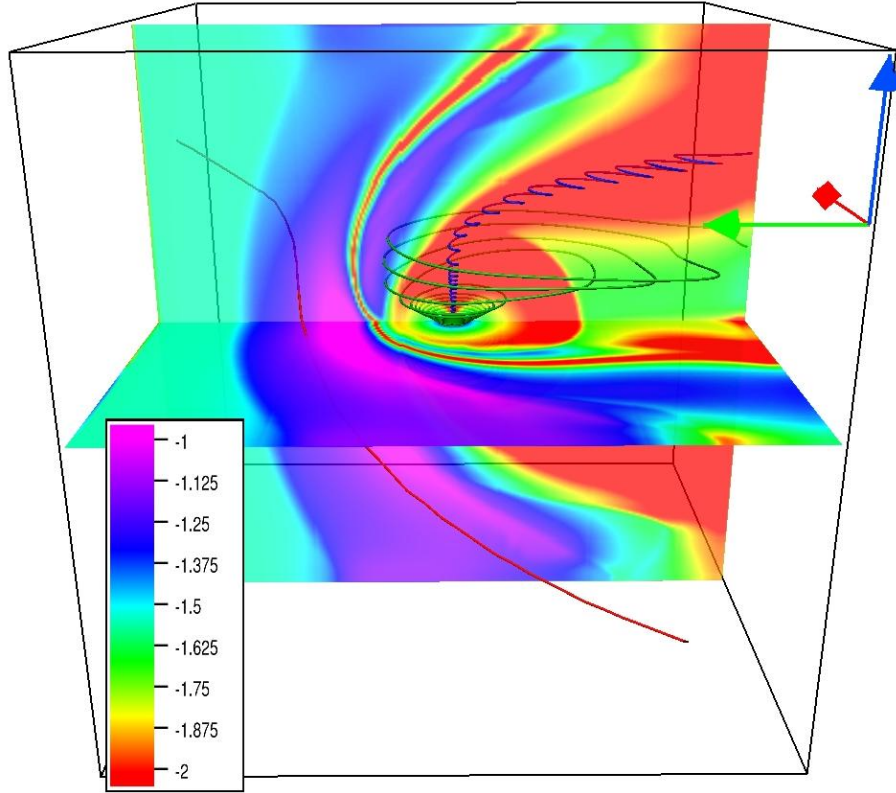


Figure 3.8: The modelled $|\vec{B}|$ (again on an inverted colour scale) in the meridional and equatorial planes of the heliosphere. Two HMF lines (blue and green lines) and a single ISM $\vec{B}$ line (red line) are also shown.

The modelled $|\vec{B}|$ is shown in Fig. 3.8 in both the meridional and equatorial regions (again, the $\log_{10}$ of the quantity is shown). Three $\vec{B}$ lines are also shown: The green and blue lines are two HMF lines originating at different latitudes, while the red line shows an ISM $\vec{B}$ line. Note the non-Parkerian HMF structure beyond the TS and the deflection of the ISM $\vec{B}$ along the HP, being draped almost parallel to it.

3.7 Summary and Conclusions

In this chapter, the 3D MHD model of *Pen et al.* [2003] was briefly discussed and tested before being applied to the heliosphere. The modelled heliospheric plasma environment is qualitatively consistent with that of more complex MHD model results, although quantitative consistency is limited by the single fluid approach adopted here. In future, additional plasma and neutral species can be added to the present model. The modelled MHD flow will be incorporated into the hybrid model discussed in Chapter 8, in order to simulate more realistic particle transport than just assuming expressions for the background plasma flow.