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Local Interstellar Parameters as They Are Inferred from Analysis of Observations Inside the Heliosphere

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Abstract This paper provides a brief summary on the current knowledge of the properties of the Circum-Heliospheric Interstellar Medium (CHISM). It discusses what can be learnt on the parameters of CHISM's components from analysis of measurements performed inside the heliosphere. The analysis is based on the kinetic-gasdynamic models of the solar wind/interstellar medium interaction. We focus the analysis on three types of diagnostics: 1) interstellar H atom number density at the heliospheric termination shock inferred from pickup ion measurements, 2) the location and time of the Voyager 1 and 2 termination shock crossings, 3) the deflection of the interstellar H atom flow inside the heliosphere as been measured by SOHO/SWAN. From these results estimations of the unknown local interstellar parameters are deduced. The parameters are the number densities of interstellar H^+ and H and the magnitude and direction of the interstellar magnetic field in the vicinity of the solar system.

Keywords Heliospheric interface · Interstellar H atoms · Voyager

1 Introduction

The goal of this paper is to provide a brief summary on our current knowledge on the parameters of the circumsolar heliospheric interstellar medium (CHISM) as they can be determined from observations inside the heliosphere and numerical modelling. The heliosphere and CHISM are separated by the heliospheric interface region that is formed in the interaction of the solar wind with the interstellar gas (Fig. 1). The interstellar charged component

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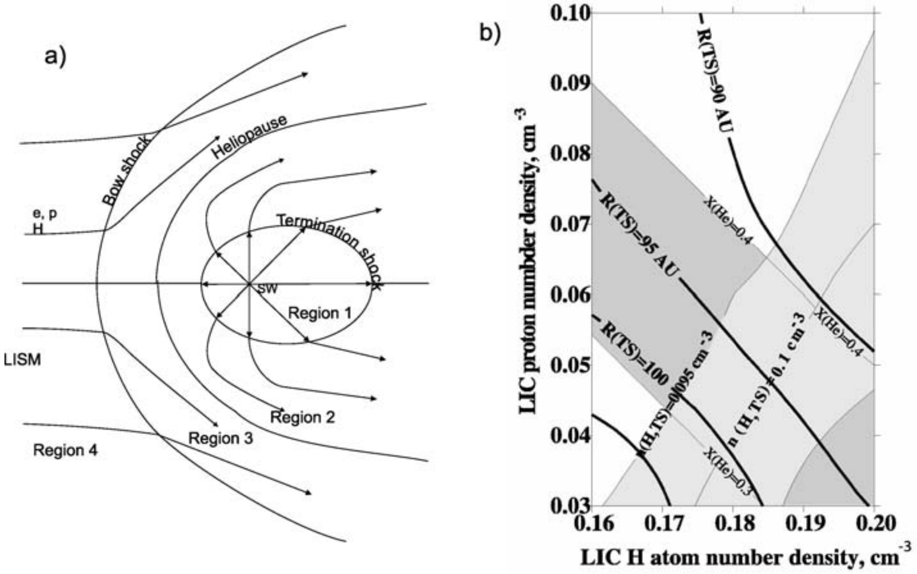

Fig. 1 **a**) Schematic view of the heliospheric interface structure. The Heliopause is the tangential discontinuity that separates the CHISM plasma from the solar wind. The termination shock and the bow shock decelerate the supersonic solar wind and the interstellar gas respectively. **b**) Results of a parametric study in the frame of a modified Baranov-Malama model (Izmodenov et al. 2003)

(electrons and protons) as well as the interstellar magnetic field are diverted around the heliopause by the interaction with the solar wind. So parameters of these components can not be measured from inside the heliosphere.

Luckily the CHISM is partly ionized. The CHISM neutral gas component consists of hydrogen (∼90%), helium (∼9%), oxygen, neon, nitrogen, and other minor components. The mean free path of the interstellar atoms is larger or similar to the size of the heliospheric interface region. Therefore, the neutrals penetrate the heliosphere where they can be measured.

The CHISM neutral component and its products (pickup ions and ACRs) are the major sources of information on the CHISM properties. Interstellar helium atoms penetrate the heliospheric interface undisturbed, because of a very weak coupling to protons. Indeed, due to the small cross sections of elastic collisions and charge exchange with protons, the mean free path of these atoms is much larger than the size of the heliospheric interface. Measurements of interstellar helium allow us to determine: 1) direction and velocity of the local interstellar flow, 2) local interstellar temperature. The most precise determination of these parameters was performed by using Ulysses/GAS direct measurements of interstellar helium atoms. Analysis of Ulysses/GAS observations (Witte 2004) results in a velocity $V_{\mathrm{CHISM}} = 26.3 \pm 0.4$ km/s with ecliptic longitude $\lambda = 74.7 \pm 0.5°$ and elevation $\beta = -5.2 \pm 0.2°$ of the CHISM inflow and a temperature $T_{\mathrm{CHISM}} = 6300 \pm 340$ K. The velocity and temperature of interstellar helium inside the heliosphere can also be obtained from measurements of backscattered solar radiation (Vallerga et al. 2004; Lallement et al. 2004a, 2004b). Independently, the velocity and temperature in the local interstellar cloud (CHISM) can be derived from the analysis of absorption features in stellar spectra (Lallement and Bertin 1992; Lallement 1996). However, this method provides only mean values along lines of sight toward nearby stars in the local interstellar medium. Comparison of the interstellar helium parameters obtained with the different methods are given in Möbius et al. (2004).

The mean free paths of interstellar hydrogen and oxygen are comparable with or larger than the characteristic size of the heliospheric interface. Therefore, similar to helium these components penetrate inside the heliosphere and can be measured. However, contrary to interstellar helium, interstellar hydrogen and oxygen are significantly disturbed in the heliospheric interface due to their coupling with protons by resonant charge exchange. The fact that these populations of interstellar atoms are disturbed in the interface allows to infer some properties of the heliospheric interface. Since the structure of the interface is determined by properties of the CHISM these properties can potentially be constrained from analysis of interstellar atom distributions inside the heliosphere. Such an analysis requires theoretical models of the solar wind interaction with the CHISM. In this paper we will combine current knowledge of the interstellar hydrogen parameters measured inside the heliosphere and theoretical models of the heliospheric interface in order to derive constraints on the remaining unknown CHISM parameters such as proton and H atom number densities, interstellar magnetic field magnitude and direction.

2 Observations from Inside the Heliosphere

Table 1 summarizes current major available diagnostics of the heliospheric interface. Most of the diagnostics are indirect and require special analysis and interpretation that is inherently model dependent. One of the most direct diagnostics of the heliospheric interface is provided by the crossings of the heliospheric termination shock (TS) by Voyager 1 and 2

Table 1 Summary of available diagnostics of the heliospheric interface and local interstellar parameters

Type of diagnostics	What is measured?	What can be determined?
Backscattered Ly-α		
SOHO/SWAN, HST	Spectral characteristics	Properties of H atom velocity distribution inside the heliosphere
Voyager, Pioneer, etc.	intensity	H number density inside the heliosphere
Pickup ions measured on board Ulysses and ACE	energy spectra	H atom number density inside the TS local interstellar composition
ACR and energetic particles	energy spectra	plasma properties in outer heliosphere local interstellar composition
Solar wind parameters measured by Voyager 2	density, velocity temperature	H atom number density inside the heliosphere
Voyager 1 and 2 crossing the TS		effective interstellar pressure; TS asymmetry
Absorption spectra toward nearby stars (HST)	Ly-alpha line spectra	constraints on the heliospheric flow (both inner and outer heliosheath)
2–3 kHz emission Voyagers		distance to the HP; plasma density gradient in the inner heliosheath

Table 2 Summary of parameters determined by using spacecraft data inside the heliosphere

Type of diagnostics	Determined parameters	References
Backscattered Ly-α		
SOHO/SWAN, HST	V(H, TS) = 22–23 km/s,	Costa et al. (1999)
	T(H, TS) = 12000 K	
	deflection of H atoms	Lallement et al. (2005)
	time-variation of H atom properties	Quemerais et al. (2008a, 2008b)
Voyager, Pioneer, etc.	$n(\mathrm{H, TS}) = 0.085\text{–}0.095\ \mathrm{cm}^{-3}$	Pryor et al. (2008)
Pickup ions measured	$n(\mathrm{H, TS}) = 0.11 \pm 0.022\ \mathrm{cm}^{-3}$	Bzowski et al. (2008)
by Ulysses and ACE	$n(\mathrm{H, TS}) = 0.10 \pm 0.01\ \mathrm{cm}^{-3}$	Geiss et al. (2006)
Solar wind parameters	$n(\mathrm{H, TS}) = 0.09 \pm 0.01\ \mathrm{cm}^{-3}$	Richardson et al. (2008)
measured by Voyager 2		
Crossing the TS by	94.1 AU in Dec 2004	Burlaga et al. (2005), Stone et al. (2005),
Voyager 1		Decker et al. (2005)
and by Voyager 2	83.7 AU in August 2007	Richardson and Stone (2008)
Absorption spectra		Wood et al. (2007, 2008)
toward nearby stars (HST)		
2–3 kHz emission measured	$n(\mathrm{e, CHISM}) = 0.04\ \mathrm{cm}^{-3}$	1.8 kHz emission cut-off
by Voyagers	∼158 AU	Gurnett et al. (2006), and ref. therein

at 94 AU in December 2004 and at 83.7 AU in August–September 2007, respectively. As it will be seen later in this paper the knowledge of the TS distances in two directions already provides significant constraints on the CHISM parameters. However, the heliosphere is essentially three dimensional and time-dependent, so two locations of the TS are not enough to determine the global 3D time-dependent structure of the heliospheric interface.

Among other diagnostics of the heliospheric interface are:

– determination of the interstellar hydrogen properties from measurements of backscattered solar Lyman-alpha radiation with SOHO, Hubble Space Telescope, Voyager 1 and 2, Pioneer 10, Cassini, Ulysses, Galileo, etc.,
– observation of pickup ion spectra on board Ulysses and ACE,
– measurement of the solar wind speed and density in the distant heliosphere on board Voyager 2,
– observation of ACRs and energetic particles on boards of the two Voyagers and other spacecraft,
– measurements of Lyman-alpha absorption spectra toward nearby stars by Hubble Space Telescope (HST)
– measurements of the 2–3 kHz emission from the distant heliosphere on board the Voyagers.

In this paper we focus on three specific results that can be inferred from remote diagnostics of the heliospheric interface (Table 2). They are 1) the location of the TS at 94 AU in Dec 2004 in direction toward Voyager 1, and at 84 AU in Aug.–Sep. 2007 in direction toward Voyager 2; 2) the number density of the interstellar H atoms in the outer heliosphere; 3) the direction of motion of the interstellar H atoms in the outer heliosphere.

As it is seen from Table 2, the H atom number density in the outer heliosphere (i.e. near the heliospheric termination shock) is established with rather good accuracy. Different diagnostic methods provide similar values for the number density.

In addition, the direction of the H atom flow and its velocity and temperature can be determined from analysis of spectral properties of the backscattered solar Lyman-alpha radiation by using hydrogen-cells that are parts of SOHO/SWAN instrument. In particular, from analysis of SOHO/SWAN data it was obtained (Lallement et al. 2005) that the inflow direction of interstellar H atoms at the TS is few degrees deflected as compared with the direction of interstellar helium. This deflection is explained by an asymmetry of the heliospheric interface structure due to influence of the interstellar magnetic field (Lallement et al. 2005; Izmodenov et al. 2005b). The H-cell technique allows also to determine the bulk speed and effective temperature of the interstellar hydrogen in the outer heliosphere (e.g. Costa et al. 1999) and their variations with the solar cycle (Quemerais et al. 2006, 2008b). Recent development in the analysis of backscattered Lyman-alpha radiation is reported in Quemerais et al. (2008a).

The analysis of Lyman-alpha absorption spectra toward nearby stars is presented in Wood et al. (2007, 2008) and will not be touched here.

3 Multi-Component Models of the Global Heliosphere

In order to put constraints on the CHISM parameters one needs to employ a theoretical model of the heliospheric interface. This section briefly reviews current kinetic-gasdynamic and kinetic-MHD models of the heliospheric interface. We restrict this discussion to the kinetic-gasdynamic models developed in the Moscow group because results of these models will be used later in this paper. Models developed by other groups are described elsewhere. Most of other group models are based on multi-fluid approach for the neutral component (Fahr et al. 2000; Zank and Mueller 2003) or ignore or oversimplified the neutral component description so far (Ratkiewicz et al. 2002; Opher et al. 2004). The exception is recent models by Heerikhuisen et al. (2006, 2008), Pogorelov et al. (2008), where the component is treated kinetically as it is done in the Moscow group models reviewed here. Note, also, that comparisons between the kinetic and multi-fluid models are given in Alexashov and Izmodenov (2005), Heerikhuisen et al. (2006), Muller et al. (2008).

Table 3 summarizes the kinetic-gasdynamic models of the solar wind interaction that includes different components (or effects) of the solar wind or CHISM. Following Baranov and Malama (1993) model all further models take into account interstellar plasma and H atom components. The H atom component is treated kinetically, while the plasma component is treated as a fluid. In addition to protons and electrons, the plasma component includes solar wind alpha particles and interstellar helium ions. These components have minor effects on the interstellar H atoms in the heliosphere but noticeable influence on the location of the heliopause (e.g. Izmodenov et al. 2003). The entire heliosphere, including the heliospheric termination shock, shows significant fluctuations over the solar cycle (Izmodenov et al. 2005a, 2008a). The interstellar magnetic field makes the heliospheric interface asymmetric and influences both shape and location the heliospheric termination shock (Izmodenov et al. 2005b). Effects of the galactic and anomalous cosmic rays on the global distribution of the H atoms and plasma in the interface are insignificant (Myasnikov et al. 2000a, 2000b; Alexashov et al. 2004), but may change the location of the TS by a few AU. A recent model by Malama et al. (2006) makes a step toward a realistic description of the heliospheric plasma, treating pickup ions as a separate kinetic component co-moving with

Table 3 Modern multi-component kinetic-gasdynamic and kinetic-MHD models of the heliospheric interface developed by Moscow group

Component or effect	Reference
Interstellar H atoms (kinetic description)	Baranov and Malama (1993), Izmodenov et al. (2001) in all model below in the table
Interstellar plasma: protons, electrons + helium ions	Baranov and Malama (1993) Izmodenov et al. (2003)
Interstellar magnetic field	Izmodenov et al. (2005b)
Galactic cosmic rays	Myasnikov et al. (2000a, 2000b)
Anomalous cosmic rays	Alexashov et al. (2004)
Solar wind (protons, electrons) + alpha particles	Baranov and Malama (1993); Izmodenov et al. (2003)
Pickup ions (kinetic description)	Malama et al. (2006)
Solar cycle variations of the solar wind	Izmodenov et al. (2005a, 2008a)
Latitudinal variations of the solar wind	Izmodenov and Alexashov, Astron. Lett., in preparation

the solar wind protons and electrons. The different distribution of the heliospheric H atoms obtained in the model leads to some changes in the shape and location of the termination shock and the heliopause as compared with the Baranov-Malama model.

4 CHISM Parameters Inferred from Data and Theory

In this section we establish constraints on the CHISM H atom and proton number densities as well as magnitude and direction of the interstellar magnetic field on the basis of the data and numerical models of the heliospheric interface reviewed above.

As it was said above we examine three particular results of the heliospheric interface models: 1) filtration of interstellar atoms in the interface; 2) position of the TS in the Voyager 1 and 2 directions; 3) deflection of the interstellar H atom flow as compared to the interstellar helium direction.

We start this analysis with the standard stationary axisymmetric Baranov-Malama model modified by Izmodenov et al. (2003) and then consider the influence of additional components or physical phenomena. A parametric study performed in the frame of the standard model for rather large ranges of interstellar proton and H atom number densities (0.032 $\mathrm{cm}^{-3} < n_{\mathrm{p,CHISM}} < 0.07\ \mathrm{cm}^{-3}$, $0.16\ \mathrm{cm}^{-3} < n_{\mathrm{H,CHISM}} < 0.20\ \mathrm{cm}^{-3}$) has shown that the filtration (penetration) factor, which is defined as $F_H = n_{\mathrm{H,TS}}/n_{\mathrm{H,CHISM}}$, varies insignificantly and is equal to 0.54 ± 0.04. Assuming according to Geiss et al. (2006) and references therein that $n_{\mathrm{H,TS}} = 0.100 \pm 0.01\mathrm{cm}^{-3}$ we get $n_{\mathrm{H,CHISM}} = 0.185 \pm 0.018\mathrm{cm}^{-3}$.

To put constraints on $n_{\mathrm{p,CHISM}}$ one can assume, for example, that the ratio of hydrogen to helium in the CHISM is 10. Then using that the ionization of helium in the CHISM is $35 \pm 5\%$ (Wolff et al. 1999) and $n_{\mathrm{He,CHISM}} = 0.015 \pm 0.0015\ \mathrm{cm}^{-3}$, one gets an estimate for the proton number density in the CHISM: $n_{\mathrm{p,CHISM}} = 0.05 \pm 0.015\ \mathrm{cm}^{-3}$ (see, Izmodenov et al. 2003).

Table 4 Results of parametric calculations

#	$n_{\mathrm{H,CHISM}}$ cm^{-3}	$n_{\mathrm{p,CHISM}}$ cm^{-3}	R(TS) AU	$F_{\mathrm{H,TS}}$[a]	$F_{\mathrm{O,TS}}$	$F_{\mathrm{N,TS}}$
1	0.16	0.032	109	0.58	0.72 (0.84)	0.80 (0.90)[b]
2	0.16	0.05	102	0.55	0.70 (0.83)	0.80 (0.90)
3	0.16	0.06	99	0.54	0.70 (0.82)	0.80 (0.90)
4	0.16	0.07	96	0.53	0.69 (0.81)	0.80 (0.90)
5	0.18	0.032	101	0.57	0.69 (0.82)	0.77 (0.90)
6	0.18	0.05	96	0.54	0.68 (0.81)	0.79 (0.89)
7	0.18	0.06	93	0.53	0.68 (0.81)	0.79 (0.89)
8	0.18	0.07	88	0.52	0.66 (0.80)	0.79 (0.89)
9	0.20	0.032	94	0.55	0.68 (0.82)	0.76 (0.89)
10	0.20	0.04	93	0.54	0.67 (0.81)	0.77 (0.89)
11	0.20	0.05	90	0.53	0.67 (0.79)	0.78 (0.89)
12	0.20	0.06	88	0.52	0.67 (0.80)	0.78 (0.89)
13	0.20	0.07	86	0.51	0.67 (0.79)	0.78 (0.88)

[a] $F_{\mathrm{A,TS}} = n_{\mathrm{A,TS}}/n_{\mathrm{A,CHISM}}$ (A = H, O, N) are the filtration factors of interstellar H, O, N atoms, respectively

[b] In parentheses we present filtration factors calculated under an assumption of reduced (by factor of 3) the electron temperature in the inner heliosheath between the TS and HP (Izmodenov et al. 2004)

In fact, detailed consideration of the filtration factors for H atoms (see Table 4) allows to establish range of possible pairs of ($n_{\mathrm{p,CHISM}}$, $n_{\mathrm{H,CHISM}}$) a little better than was shown above. This range is shown in Fig. 1 as the intersection of two shaded areas.

Additional constraints on $n_{\mathrm{p,CHISM}}$ and $n_{\mathrm{H,CHISM}}$ can be obtained from the location of the heliospheric termination shock. For example, if in the frame of a stationary axisymmetric model the TS is located at 95 AU (see Fig. 1) then the relation between $n_{\mathrm{p,CHISM}}$ and $n_{\mathrm{H,CHISM}}$ can be easily established: $n_{\mathrm{p,CHISM}} + 1.15\, n_{\mathrm{H,CHISM}} = 0.26$. (Here both $n_{\mathrm{p,CHISM}}$ and $n_{\mathrm{H,CHISM}}$ in cm^{-3}.) Assuming $n_{\mathrm{H,CHISM}} = 0.185 \pm 0.018$ cm^{-3} the ratio gives $n_{\mathrm{p,CHISM}} = 0.05 \pm 0.016$ cm^{-3}. This additional estimation of $n_{\mathrm{p,CHISM}}$ is independent of the H/He ratio and the helium ionization in the CHISM, but depends on the H atom number density inferred from pickup observations and on the model of the heliospheric interface.

In fact it is possible to determine $n_{\mathrm{p,CHISM}}$ independently from pickup observations. One of the possible additional diagnostics consists of spectral observations of backscattered Lyman-alpha radiation (e.g. Quemerais et al. 2006 and references therein) that allow to infer the temperature and velocity of H atoms at the termination shock (e.g. Costa et al. 1999).

To choose a final subset of possible ($n_{\mathrm{p,CHISM}}$, $n_{\mathrm{H,CHISM}}$) values some additional diagnostics are needed. This could be, for example, the temperature and velocity of the interstellar H atoms at the TS inferred from spectral measurements of backscattered Lyman-alpha radiation (e.g. Quemerais et al. 2006).

The method for obtaining $n_{\mathrm{p,CHISM}}$ and $n_{\mathrm{H,CHISM}}$ from remote observations, as presented above, would be straightforward in the case of an axisymmetric and stationary heliospheric interface. However, this is not a realistic situation. In fact, the heliosphere is breathing due to solar cycle variations of the solar wind dynamic pressure (e.g. Izmodenov et al. 2005a, 2008a). In addition, the interstellar magnetic field and heliolatitudinal asymmetry of the solar wind break the axis symmetry of the flow in the heliospheric interface (Lallement et al. 2005; Izmodenov et al. 2005b; Pogorelov et al. 2008).

Figure 2 shows fluctuations of the heliospheric termination shock in a time-dependent axisymmetric model of the heliospheric interface that takes into account the solar cycle variations of the solar wind parameters (Izmodenov et al. 2008a). The figure presents variations of the heliospheric termination shock distance for the upwind direction (black curve),

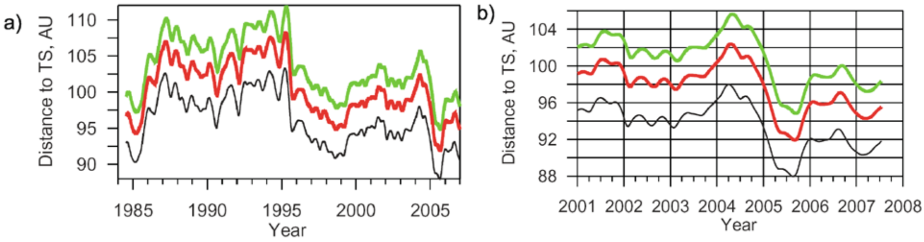

Fig. 2 **a** Distance to the heliospheric termination shock as function for the upwind direction (*black curve*), and directions of Voyager 1 and 2 (*red* and *green curves*, respectively). **b** Same as **a** zoomed for 2001–2008

and directions of Voyager 1 and 2 (red and green curves, respectively). The calculations were performed with the CHISM velocity and temperature that corresponds to Ulysses measurements of interstellar helium. Proton and H atom number densities were adopted as $n_{\mathrm{p,CHISM}} = 0.06\ \mathrm{cm}^{-3}$, $n_{\mathrm{H,CHISM}} = 0.18\ \mathrm{cm}^{-3}$. The solar wind parameters at the Earth orbit were taken from ONMI-2 Web site. Details for the model formulation and the boundary conditions are given in Izmodenov et al. (2008a).

As can be seen from Fig. 2, the axisymmetric time-dependent kinetic-gasdynamic model predicts that the distances to the heliospheric termination shock toward Voyager 1 in 2004 and toward Voyager 2 in 2007 are equal to 98 AU. For comparison, the actual crossing of the TS by Voyager 1 was at 94 AU in Dec 2004 and by Voyager 2 at ~84 AU in August–September 2007. Note, that the same distances to the termination shock in the Voyager 1 and 2 directions obtained in the time-dependent model is a coincidence (Fig. 2) that appears to come from a combination of spatial and temporal effects.

In view of this result, what are possible physical reasons for the difference between the theoretical predictions and observed distances to the heliospheric termination shock? There are many physical effects that may be responsible for the difference of ~4 AU in direction toward Voyager 1. For example, effects of galactic cosmic rays (Myasnikov et al. 2000a, 2000b) or interstellar magnetic field (Izmodenov and Alexashov 2006) may move the termination shock closer to the Sun by several AU. Conversely, the influence of anomalous cosmic rays (Alexashov et al. 2004) leads to an increase of the distance toward the termination shock.

Consideration of the multi-component nature of the heliospheric plasmas as it was introduced by Malama et al. (2006) also leads to an outward shift of the TS by 5 AU as compared with the one-fluid plasma component model by Izmodenov et al. (2003). In fact, the latter model is more realistic than a one-component plasma model because many observations show that pickup protons are not assimilated into the plasma component. The different (from Baranov-Malama model) distribution of solar wind and pickup protons in the heliosphere results in a different distribution of H atoms throughout the heliosphere. As a result of this process more energy is removed (by energetic neutrals that have a long mean free path) from the inner heliosheath as compared with models with one plasma component. This results in the displacement of the TS outward and of the heliopause inward. Therefore, under the same boundary conditions the multi-component model predicts the heliospheric termination shock at 103 AU. The situation can be improved by increasing the interstellar pressure in the models by increasing proton and/or H atom number densities. Another way to increase the total interstellar pressure is to take into account an interstellar magnetic field in the model.

Apparently, a need to introduce an *inclined* interstellar magnetic field becomes evident after considering the distance at which Voyager 2 crossed the heliospheric termi-

Table 5 Positions of the TS, HP and thickness of the inner heliosheath towards Voyager 1, Voyager 2 and upwind

	R_{TS}			R_{HP}			Heliosheath thickness		
	$\theta = 0$	V1	V2	$\theta = 0$	V1	V2	$\theta = 0$	V1	V2
no MF	96.0	99.0	104.0	157	167.2	181.0	61.0	68.2	77.0
$\alpha = 0$	98.5	100.9	104.7	169	174.6	183.3	70.5	73.7	78.6
$\alpha = 30$	88.5	92.7	92.8	149	162.3	156.6	60.5	69.6	63.8
$\alpha = 45$	83	86.9	87.6	136	147.1	144.8	53.0	60.2	57.2
$\alpha = 60$	81.6	85.2	86.6	130	139.8	140.5	48.4	54.6	53.9
$\alpha = 90$	80	82.5	87.1	128.6	133.6	148.1	48.6	51.5	61

nation shock. It is 84.7 AU, i.e. ~9 AU closer compared with the Voyager 1 crossing, while the axisymmetric time-dependent model predicts similar distances toward both directions. Any adjustments of the termination shock distance made within axisymmetric models can not explain the ~9 AU difference in the termination shock distance toward Voyager 1 and 2 as was measured. Therefore, an asymmetry of the heliospheric interface region is needed. Moreover, as it was mentioned above, the asymmetry is needed also to explain the deflection of the interstellar H atom flow in the heliosphere relative to the direction of interstellar helium (Lallement et al. 2005). The deflection is mainly associated with the effects of the interstellar magnetic field (Izmodenov et al. 2005b; Izmodenov and Alexashov 2006).

Table 5 presents distances to the heliospheric termination shock and to the heliopause and the thickness of the inner heliosheath obtained with our 3D kinetic-MHD models that include effects of the interstellar magnetic field (IsMF) (Izmodenov and Alexashov 2006). The distances are shown toward the Voyager 1 and 2 directions. To calculate the cases with the interstellar magnetic field inclined to the direction of the relative Sun/CHISM motion we assume that the interstellar magnetic field is in the plane determined by the velocity vectors of interstellar H and interstellar He (see, Lallement et al. 2005).

For an axisymmetric stationary heliosphere with no IsMF the TS is ~5 AU farther toward Voyager 2 as compared with Voyager 1 because Voyager 2 is farther from the upwind direction. In the case when the direction of the interstellar magnetic field coincides with the direction of CHISM's flow the interaction region remains axisymmetric. However, the difference of the distances to the termination shock in the Voyager 1 and 2 direction is smaller as compared to the model with no IsMF. This effect is connected with the shape of the heliopause, which is more distant from the Sun in the upwind direction and closer sidewind. In the presence of IsMF the heliopause is closer to a pencil-like shape.

In the 3D MHD case for $\alpha = 30, 45°$ (α is the angle between CHISM velocity vector and vector of the IsMF) the distances to the TS in the V1 and V2 direction become similar (Table 5). The difference of the heliospheric termination shock distances toward Voyager 1 and 2 increases with increasing angle α. In the case of $\alpha = 90°$ the heliospheric interface becomes axisymmetric. Therefore, the comparison of the axisymmetric kinetic-gasdynamic stationary model with a 3D kinetic-MHD stationary models suggests that the interstellar magnetic field may help to reduce the TS distance in the direction of Voyager 2 as compared with its distance toward the direction of Voyager 1. For $B_{CHISM} = 2.5$ μG (under the assumption that the vector of the IsMF lies in the plane determined by the directions of the interstellar helium and hydrogen flow) the TS distance at Voyager 2 can be close to the distance at Voyager 1 for $\alpha = 30–45°$. For $\alpha = 30°$ the TS is ~6 AU closer to the Sun toward

Voyager 1 direction as compared with a corresponding model without the interstellar magnetic field and in the Voyager 2 direction the TS is closer by ∼11 AU. Combining this result with time-dependent modelling of the heliosphere we obtain 92 AU for the TS distance toward Voyager 1 in 2004 and 87 AU toward Voyager 2 in 2007. For $\alpha = 45°$ the agreement with the model gets worse, ∼86 AU for the TS distance toward Voyager 1, i.e. significantly closer than 94 AU. The model's distance in the direction toward Voyager 2 is 82 AU in 2007. Therefore, we conclude that the model with $\alpha = 30°$ provides better agreement with actual crossings. In fact, to get perfect agreement between the model and data the TS should be 2 AU further in the Voyager 1 direction and 3 AU closer to the Sun in the Voyager 2 direction. This may require a somewhat stronger magnetic field and smaller value of α. Such possible solutions were demonstrated by Izmodenov et al. (2008b) already after the paper was prepared. Note, however, that such solutions are possible if employed cross section is different from the cross section used in this paper (see, Izmodenov et al. 2008b).

In conclusion, the magnitude and direction of the interstellar magnetic field can indeed be inferred from the deflection of the interstellar H atom flow as compared with the direction of the interstellar helium flow. Estimations performed by Izmodenov et al. (2005b), Izmodenov and Alexashov (2006) have shown that models with $B_{\mathrm{CHISM}} = 2.5$ μG, and $\alpha = 30$–$45°$ provide values for the deviation that are in agreement with the amount obtained from analysis of the SOHO/SWAN data.

5 Conclusions and Perspectives

In this paper we performed an analysis of data obtained from space experiments inside the heliospheric termination shock to obtain the local interstellar parameters such as proton and H atom number densities, magnitude and direction of interstellar magnetic field. We used the H number density at the termination shock determined from Ulysses pickup measurements, the Voyager 1 and Voyager 2 crossings of the heliospheric termination shock, and the deflection of the H atom flow direction inside the heliosphere from analysis of SOHO/SWAN data in comparison with the pristine interstellar wind flow as obtained from the observations. The study was based on results of 2D time-dependent kinetic-gasdynamic models (Izmodenov et al. 2005a) and stationary 3D kinetic-MHD models (Izmodenov et al. 2005b).

We conclude that $n_{\mathrm{H,CHISM}} = 0.185 \pm 0.018\ \mathrm{cm}^{-3}$, $n_{\mathrm{p,CHISM}} = 0.05 \pm 0.016\ \mathrm{cm}^{-3}$, $B_{\mathrm{CHISM}} = 2.5$–3.5 μG, $\alpha_{\mathrm{CHISM}} = 15$–$30$ deg.

These conclusions are model dependent and further advancement of the heliospheric interface models will provide even better constraints on the CHISM parameters. Tightening the constraints will require extended parametric calculations, including magnitudes of the interstellar magnetic field larger than 2.5–3 μG and angles between the CHISM flow and the IsMF direction smaller than 30 deg. In fact new model calculations by Izmodenov et al. (2008b) show that $B_{\mathrm{CHISM}} = 4.4$ and μG, $\alpha_{\mathrm{CHISM}} = 15$ deg is also possible solution.

Perspectives. The heliospheric interface is a great example of exploration by using a combination of different experimental diagnostics and intensive multi-component modelling.

In fall 2008, the Interstellar Boundary Explorer (IBEX) will be launched. The instrumentation implemented on the spacecraft will provide maps of fluxes and energy spectra of the heliospheric energetic neutral atoms (ENAs). ENAs originate in the region of the inner heliosheath between the heliospheric termination shock and the heliopause. 3D MHD-kinetic calculations show an asymmetry of the inner heliosheath and in the fluxes of heliospheric ENAs. Therefore, the ENA maps will provide new diagnostics of the global asymmetry of the heliospheric interface. Future expectations are also connected with the planned measurement of interstellar oxygen atoms with the IBEX/Lo sensor (Möbius et al. 2008). Interstellar oxygen is coupled to the plasma component in the heliospheric interface (Izmodenov et al. 1997, 1999, 2004; Izmodenov 2007) and may serve as an additional tracer of the heliospheric interface properties and local interstellar parameters.

In addition a large amount of information has been collected over the solar cycle by SOHO/SWAN instrument and new direct information from the inner heliosheath is continuously provided by Voyager 1 and 2.

Existing and new observations challenge theoreticians to develop more detailed and precise models of the heliospheric interface. With modern computers and previous modeling expertise complete 3D non-stationary and self-consistent multi-component kinetic-MHD models of the heliospheric interface are possible in the near future. However, since heliospheric hydrogen atoms have mean free paths comparable with or larger than the size of the heliospheric interface high-energy tails (e.g. Fisk and Gloeckler 2007) may become dynamically important. Therefore, a kinetic description should be employed in the models for both neutral and plasma components. Importance of the kinetic description for the plasma component is seen in the results of the first self-consistent model of the heliospheric interface that employs a kinetic description for both neutral and plasma components (Malama et al. 2006).

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