

EFFECTS OF INTERSTELLAR AND SOLAR WIND IONIZED HELIUM ON THE INTERACTION OF THE SOLAR WIND WITH THE LOCAL INTERSTELLAR MEDIUM

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Received 2003 June 27; accepted 2003 July 15; published 2003 July 30

ABSTRACT

The Sun is moving through a warm (~ 6500 K) and partly ionized local interstellar cloud (LIC) with a velocity of ~ 26 km s⁻¹. Recent measurements of the ionization of the LIC (Wolff, Koester, & Lallement) suggest that interstellar helium in the vicinity of the Sun is 30%–40% ionized and that interstellar hydrogen is less ionized. Consequently, interstellar helium ions contribute up to 50% of the total dynamic pressure of the ionized interstellar component. Up to now, interstellar helium ions have been ignored in existing models of the heliospheric interface. In this Letter, we present results of a new model of the interaction of the solar wind with the interstellar medium; this model takes into account interstellar helium ions. Using the results of this model, we find that the heliopause, termination, and bow shocks are closer to the Sun than the model results that ignore He ions. The influence of interstellar helium ions is partially compensated by solar wind α -particles, which are taken into account in our new model as well. Finally, with our new model, we place constraints on the plausible location of the termination shock.

Subject headings: interplanetary medium — ISM: atoms — solar wind

1. INTRODUCTION

The solar wind interacts with the local interstellar cloud (LIC) to form the heliospheric interface, which separates the pristine interstellar medium from the unperturbed solar wind. The solar wind meets the interstellar charged component at the heliopause (HP), where the solar wind pressure balances the pressure of the LIC. Since the solar wind is a supersonic flow, the heliospheric termination shock (TS) should be formed to make the solar wind subsonic before it reaches the HP. Because the interstellar flow is also supersonic ($V_{\text{LIC}} \sim 26$ km s⁻¹, $T_{\text{LIC}} \sim 6500$ K), a bow shock (BS) may be formed in the interstellar medium. The idealized structure of the heliospheric interface is shown in Figure 1.

Recent models of the heliospheric interface take into account the multicomponent nature of both the LIC and the solar wind (see, e.g., Baranov & Malama 1993; Alexashov et al. 2000; Fahr, Kausch, & Scherer 2000; Myasnikov et al. 2000; Izmodenov, Gloeckler, & Malama 2003; for review, see Zank 1999). Up to now, interstellar helium ions were ignored in the multicomponent modeling of the solar wind interaction with the LIC. Recent measurements of interstellar helium atoms (Witte, Banaszekiewicz, & Rosenbauer 1996) and interstellar He pickup ions (Gloeckler & Geiss 2001) inside the heliosphere as well as of the interstellar helium ionization (Wolff, Koester, & Lallement 1999) allow us to estimate the number density of interstellar helium ions to be 0.008–0.01 cm⁻³. Current estimates of proton number density in the LIC fall in the range of 0.04–0.07 cm⁻³. Since helium ions are 4 times heavier than protons, the dynamic pressure of the ionized helium component is comparable to the dynamic pressure of the ionized hydrogen component. Therefore, interstellar ionized helium cannot be ig-

nored in the modeling of the heliospheric interface. In this Letter, we present results of our new model, which for the first time takes into account interstellar ionized helium. Simultaneously with interstellar ionized helium, we took into account solar wind α -particles, which constitute 2.5%–5% of the solar wind and, therefore, produce 10%–20% of the solar wind dynamic pressure.

2. MODEL

In this work, we start with the global model of the heliospheric interface developed by the Moscow group (Baranov & Malama 1993; Izmodenov et al. 1999; Alexashov et al. 2000; Myasnikov et al. 2000; Izmodenov & Alexashov 2003; Izmodenov et al. 2003; for review, see Izmodenov 2001) and introduce interstellar ionized helium (He⁺) and solar wind α -particles (He⁺⁺) into the model. We consider all plasma components (electrons, protons, pickup ions, interstellar helium ions, and solar wind α -particles) as one fluid with the total density ρ and bulk velocity v . This one-fluid approximation assumes that all ionized components have the same temperature T . Although this assumption cannot be made in the case of the solar wind, the one-fluid model is based on mass, momentum, and energy conservation laws and predicts the plasma bulk velocity and locations of the shocks very well.

The plasma is quasi-neutral; i.e., $n_e = n_p + n_{\text{He}^+}$ for the interstellar plasma, and $n_e = n_p + 2n_{\text{He}^{++}}$ for the solar wind. We ignore the magnetic field. While the interaction of interstellar H atoms with protons by charge exchange is important, for helium ions the process of charge exchange is negligible because of the small cross sections for the charge exchange of helium atoms. Hydrodynamic Euler equations for the charged component are solved self-consistently with the kinetic equation for the interstellar H atom component. The temperature of the plasma is determined from the equation of state $p = 2(n_p + n_{\text{He}^+})kT$ for the interstellar plasma and $p = (2n_p + 3n_{\text{He}^{++}})kT$ for the solar wind. To calculate sources of mass, momentum, and energy into the charged component that are due to the charge exchange of H atoms with protons and photoionization and electron-impact ionization processes, we need to know n_p in addition to the total plasma density. (Expressions for the sources can be found, for example, in Izmodenov &

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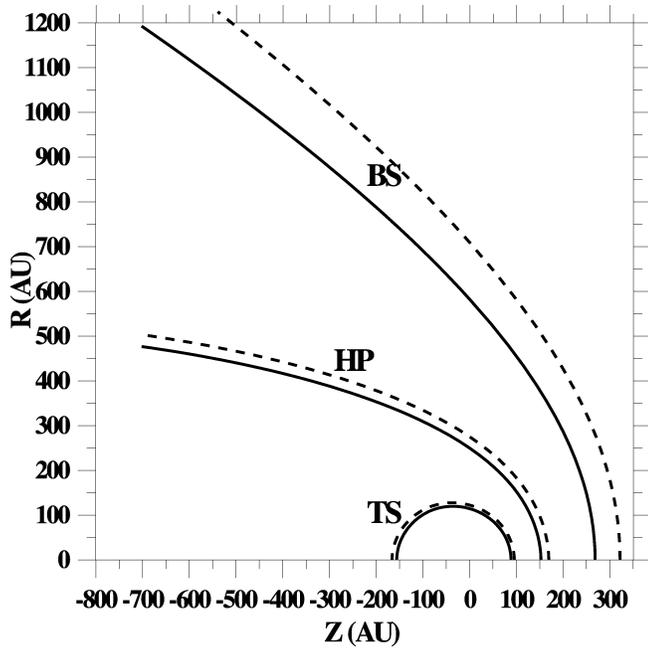


FIG. 1.—Sketch of the idealized structure of the heliospheric interface (the region of the interaction of the solar wind with the LIC) based on results of numerical modeling. We used the following interstellar parameters: (1) atomic hydrogen number density ($=0.18 \text{ cm}^{-3}$), (2) proton number density ($=0.06 \text{ cm}^{-3}$), (3) gas temperature ($=6500 \text{ K}$), and (4) gas speed (relative to the Sun) ($=26.4 \text{ km s}^{-1}$), and the following average solar wind parameters: (5) solar wind density at 1 AU ($=7.39 \text{ cm}^{-3}$) and (6) speed ($=432 \text{ km s}^{-1}$). A discussion of, and references for, the chosen parameters are given in the text. The dashed curves correspond to model 1, and the solid curves correspond to model 2 (see Table 1).

Alexashov 2003.) We solve the continuity equations for He^+ in the interstellar medium and for α -particles in the solar wind. Then the proton number density can be calculated as $n_p = (\rho - m_{\text{He}} n_{\text{He}}) / m_p$. Here n_{He} denotes the He^+ number density in the interstellar medium, and He^{++} the number density in the solar wind. The velocity distribution of H atoms $f_{\text{H}}(\mathbf{r}, \mathbf{w}_{\text{H}}, t)$ is calculated from the linear kinetic equation introduced in Baranov & Malama (1993). The plasma and neutral components interact mainly by charge exchange. However, photoionization, solar gravitation, and radiation pressure, which are taken into account in the governing equations, are important at small heliocentric distances. Electron-impact ionization may be important in the inner heliosheath, the region between the TP and the HP.

3. BOUNDARY CONDITIONS

The boundary conditions are the following. At the Earth orbit, we assume that solar wind is spherically symmetric, which makes our model axisymmetric, and we use *IMP-8* data⁵ averaged over several solar cycles for the solar wind parameters: $n_{p,E} = 7.39 \text{ cm}^{-3}$, $V_{\text{sw},E} = 432 \text{ km s}^{-1}$. The number density of solar wind α -particles is varied in our calculations from 0% to 4.5% of the solar wind proton number density. The total density and pressure of the solar wind at the inner boundary at 1 AU are then

$$\rho_E = m_p n_{p,E} + m_{\text{He}} n_{\text{He}^{++},E},$$

$$p_E = (2n_{p,E} + 3n_{\text{He}^{++},E})kT_E,$$

respectively.

Among the interstellar parameters influencing the heliospheric interface structure, the LIC velocity relative to the Sun and the temperature of the local interstellar gas are now well established by direct measurements of interstellar helium atoms with the GAS instrument on *Ulysses* (Witte et al. 1996). Unlike interstellar hydrogen, atoms of interstellar helium penetrate the heliospheric interface nearly undisturbed because of the negligible strength of the coupling with protons due to the small cross sections of elastic collisions and charge exchange. Based on these measurements, we take in this Letter the temperature of the interstellar gas to be 6500 K and the speed of the LIC relative to the Sun as 26.4 km s^{-1} . The remaining three input parameters required to calculate the heliospheric interface structure are the number densities of interstellar protons, $n_{p,\text{LIC}}$, of interstellar helium ions, $n_{\text{He}^+,\text{LIC}}$, and of H atoms, $n_{\text{H},\text{LIC}}$. To find good estimates of these important LIC parameters, we use (1) our measurements of the atomic H density at the TS ($=0.100 \pm 0.008 \text{ cm}^{-3}$), (2) measurements of the LIC atomic He density ($=0.015 \pm 0.002 \text{ cm}^{-3}$; Gloeckler & Geiss 2001; M. Witte 2002, private communication), (3) the standard universal ratio of the total H to He, $(n_{p,\text{LIC}} + n_{\text{H},\text{LIC}}) / (n_{\text{He}^+,\text{LIC}} + n_{\text{He},\text{LIC}}) = 10$, and (4) measurements of the local interstellar helium ionization fraction, $n_{\text{He}^+,\text{LIC}} / (n_{\text{He}^+,\text{LIC}} + n_{\text{He},\text{LIC}}) = 0.35 \pm 0.05$ (Wolff et al. 1999). Previously, a similar method was used to determine interstellar H atom and proton number densities by Lallement (1996), Gloeckler, Fisk, & Geiss (1997), and Izmodenov et al. (2003). With these constraints, we find that the heliospheric interface model with $n_{\text{H},\text{LIC}} = 0.18 \pm 0.02 \text{ cm}^{-3}$, $n_{p,\text{LIC}} = 0.06 \pm 0.015 \text{ cm}^{-3}$, and $n_{\text{He}^+,\text{LIC}} = 0.009 \text{ cm}^{-3}$ provides the best fit to Solar Wind Ion Composition Spectrometer (SWICS) *Ulysses* pickup hydrogen data. The interstellar hydrogen ionization fraction derived from our results is in agreement with recent calculations of the photoionization of interstellar matter within 5 pc of the Sun (Slavin & Frisch 2002).

The total density and pressure of the interstellar gas are calculated to be

$$\rho_{\text{LIC}} = m_p n_{p,\text{LIC}} + m_{\text{He}} n_{\text{He}^+,\text{LIC}},$$

$$p_{\text{LIC}} = 2(n_{p,\text{LIC}} + n_{\text{He}^+,\text{LIC}})kT_{\text{LIC}},$$

respectively.

4. RESULTS

To evaluate the possible effects of both interstellar ions of helium and solar wind α -particles, we performed parametric model calculations with eight different sets of boundary conditions, given in Table 1. Calculated locations in the upwind direction of the TS, the HP, and the BS are given for each model in the last three columns of Table 1, respectively. In the first six models, we assume that $n_{p,\text{LIC}} = 0.06 \text{ cm}^{-3}$ and $n_{\text{H},\text{LIC}} = 0.18 \text{ cm}^{-3}$. Model 1 does not include either interstellar ionized helium or solar wind α -particles. Effects of interstellar ionized helium can be seen by comparing the results of model 1, with no ionized interstellar He, with the results of model 2, in which a 37.5% ionization of interstellar helium is assumed.

⁵ *IMP-8* is the last *IMP* (*Interplanetary Monitoring Probe*) spacecraft. Unfortunately, it was turned off in 2001 October.

TABLE 1

SETS OF MODEL PARAMETERS AND LOCATIONS OF THE TS, HP, AND BS
IN THE UPWIND DIRECTION

Model	$n_{\text{H,LIC}}$ (cm^{-3})	$n_{\text{p,LIC}}$ (cm^{-3})	$n_{\alpha,\text{sw}}/n_{e,\text{sw}}$ (%)	χ_{He}^a	$R(\text{TS})$ (AU)	$R(\text{HP})$ (AU)	$R(\text{BS})$ (AU)
1	0.18	0.06	0	0	95.6	170	320
2	0.18	0.06	0	0.375	88.7	152	270
3	0.18	0.06	2.5	0	100.7	176	330
4	0.18	0.06	2.5	0.150	97.5	168	310
5	0.18	0.06	2.5	0.375	93.3	157	283
6	0.18	0.06	4.5	0.375	97.0	166	291
7	0.20	0.04	0	0	95.0	183	340
8	0.20	0.04	2.5	0.375	93.0	171	290

^a $\chi_{\text{He}} = \text{He II}/(\text{He I} + \text{He II})$.

Interstellar helium ions increase the interstellar dynamic pressure by 60% and the interstellar thermal pressure by 15% in model 2 as compared with model 1. This additional interstellar pressure pushes the BS, the HP, and the TS toward the Sun (e.g., from the dashed curve to the solid curves of Fig. 1). In model 2, the HP is ~ 20 AU, and the TS is ~ 7 AU; these are closer to the Sun than those in model 1. The influence on the BS location is even stronger. The BS is ~ 50 AU closer to the Sun than the BS in model 1. This strong displacement of the BS toward the Sun is also connected with the fact that the Mach number is larger when ionized helium is taken into account. Indeed,

$$M = \frac{V}{\sqrt{\gamma P/\rho}} = V \sqrt{\frac{n_{\text{p,LIC}} + 4n_{\text{He}^+,\text{LIC}}}{n_{\text{p,LIC}} + n_{\text{He}^+,\text{LIC}}} \frac{m_p}{2\gamma k_B T_{\text{LIC}}}} = 2.3,$$

as compared with $M = 1.97$ for model 1. Here m_p and k_B are the proton mass and the Boltzmann's constant, respectively. The plasma compression at the BS is 1.45 for model 2 and 1.22 for model 1. Higher compression of the interstellar plasma at the BS and the corresponding reduction of the size of the outer heliosheath—the distance between the BS and the HP—make the optical depth for interstellar H atoms in the interface about the same for models 1–6. The resulting filtration of interstellar hydrogen atoms in the interface is therefore about the same in all of the first six models. The effects of the solar wind α -particles are seen from a comparison of the results of model 1 with those of model 3. The influence of solar wind α -particles on the locations of the HP and shocks is opposite to the influence of interstellar helium ions discussed above. Since solar wind α -particles constitute only 10%–18% of the solar wind dynamic pressure, their influence is less pronounced. The HP and the TS move out by ~ 6 and ~ 5 AU from the Sun, respectively.

The net effect of both the interstellar ionized helium and solar wind α -particles is seen by comparing models 4–6. Model 5 corresponds to 37.5% of the interstellar helium ionization and 2.5% of the solar wind α -particle abundance. The influence of interstellar helium ions on the locations of the HP, the BS, and the TS is stronger than the influence of the solar wind α -particle component. The HP is located ~ 13 AU closer to the Sun in model 5 than in model 1. We note with interest that Gurnett et al. (1993) and Gurnett & Kurth (1995), analyzing heliospheric radio emission events of 1983–1984 and 1992–1994 at the plasma cutoff frequency 2.2–2.8 kHz detected by *Voyagers 1* and 2, estimated the average distance to the HP to be 158 AU, close to the HP distance we find for model 5. The BS is closer to the Sun by ~ 40 AU. At the same time, the TS location is only ~ 2 AU closer to the Sun. For smaller interstellar He ion-

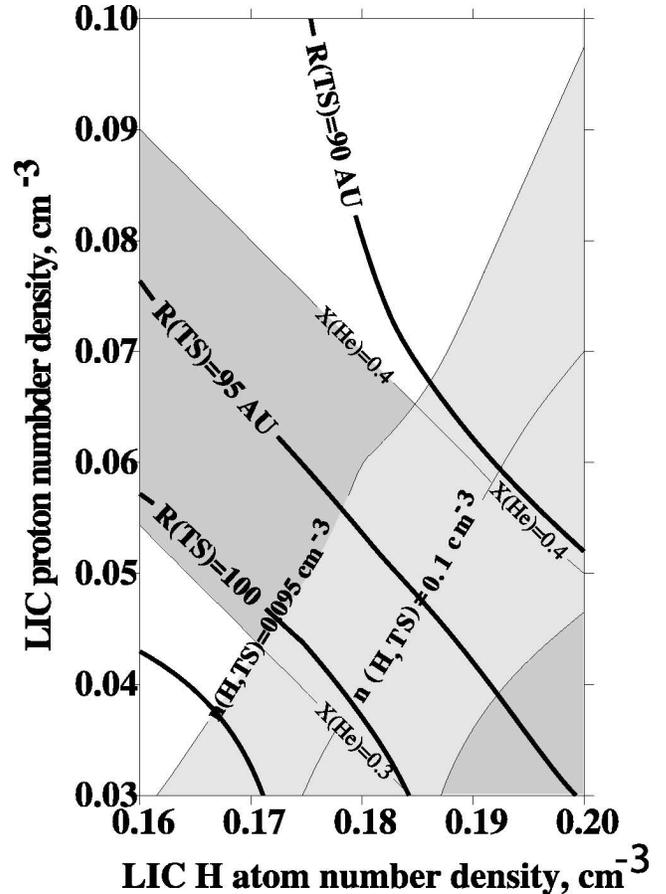


FIG. 2.—Contour plots of the interstellar H atom number density at the TS, the LIC helium ionization fraction, and the TS location in the upwind direction.

ization (model 4) or a higher abundance of solar wind α -particles (model 6), the TS is 4–5 AU farther from the Sun (as compared with model 5). To estimate the influence of the interstellar ionized helium component in the case of a smaller hydrogen ionization, we took $n_{\text{p,LIC}} = 0.04 \text{ cm}^{-3}$ and $n_{\text{H,LIC}} = 0.20 \text{ cm}^{-3}$ in models 7–8. Expectedly, the effect on the locations of the HP and the TS is about the same as previously (see Table 1). The BS is ~ 50 AU closer in model 8 than in model 7.

5. IMPLICATIONS OF THE TS LOCATION

Using our model and boundary conditions described above, we performed parametric studies by varying the interstellar proton and hydrogen atom number densities in the ranges of 0.03–0.1 and 0.16–0.2 cm^{-3} , respectively. The interstellar helium ion number density was calculated by using an interstellar helium atom number density of 0.015 cm^{-3} and the interstellar H/He ratio of 10. Figure 2 shows the results of our calculations, which are displayed as contour isolines of (1) the neutral hydrogen density at the TS, (2) the LIC helium ionization fraction, and (3) the TS location in the upwind direction on a $(n_{\text{H,LIC}}, n_{\text{p,LIC}})$ -coordinate plane. The shaded areas show (a) the $n_{\text{H,TS}}$ range of 0.095–0.105 cm^{-3} , which corresponds to a recent *Ulysses* determination (Gloeckler & Geiss 2001), and (b) the interstellar helium ionization fraction range of 0.3–0.4 derived from line-of-sight *Extreme Ultraviolet Explorer* measurements toward white dwarf stars in the local interstellar medium (Wolff et al. 1999). The intersection of the two shaded areas gives a likely range of interstellar proton and atomic hydrogen number densities compatible with observations. Using long-term av-

erages of *IMP-8* solar wind parameters places the average TS location at more than 90 AU in the upwind direction and at more than 95 AU in the direction of *Voyager 1* for all pairs of $(n_{\text{H,LIC}}, n_{\text{p,LIC}})$ in this darker shaded area. Solar-cycle variations of the solar wind ram pressure lead on average to a 7–8 AU deviation of the TS distance around its mean value (Izmodenov et al. 2003). In 2002, the TS had a minimal location (Izmodenov et al. 2003), which, according to our model calculations, should not have been less than 87–88 AU under average solar wind conditions at that time of the solar cycle. Based on measurements of the low-energy particle fluxes, spectra, and composition by the *Voyager 1* Low Energy Charged Particle instrument and of an indirect determination of the solar wind speed using particle anisotropy measurements, Krimigis, Decker, & Roelof (2003) reported the probable crossing of the TS by *Voyager 1* at 85 AU in the summer of 2002 and the return to the TS upstream region about 6 months later. Temporary and probably localized excursions of the TS inward by a few AU beyond our minimum value cannot be ruled out by our calculations since they could result from an anomalously low solar wind ram pressure and possibly other causes. However, should future measurements show that the TS location is consistently less than what we calculate here, then a revision of the LIC He ionization to higher values and/or a stronger local interstellar magnetic field may be required.

6. SUMMARY AND CONCLUSIONS

We studied the influence of the interstellar ionized helium component on the heliospheric interface for the first time. This component may create up to 50% of the total dynamic pressure

of the interstellar ionized component. It is shown that the HP, the TS, and the interstellar BS are closer to the Sun when the influence of interstellar helium ions is taken into account. This effect is partially compensated for by the additional solar wind α -particle pressure that we also took into account in our model. The net result is as follows: the HP, the TS, and the BS are closer to the Sun by ~ 12 , ~ 2 , and ~ 30 AU, respectively, in model 5, which takes into account both interstellar helium ions and solar wind α -particles, than in model 1, which ignores these ionized helium components. We also found that both interstellar ionized helium and solar wind α -particles do not influence the filtration of the interstellar H atoms through the heliospheric interface.

We use our model to determine a plausible range of $(n_{\text{H,LIC}}, n_{\text{p,LIC}})$ compatible with (1) $n_{\text{H,TS}} = 0.1 \pm 0.05 \text{ cm}^{-3}$ determined by *Ulysses*/SWICS and (2) the ionization of interstellar helium 0.35 ± 0.05 . Using our model, we found that the lower limit (1σ) of the TS location in the direction of *Voyager 1* is 88 AU. While temporary and localized motions of the TS position as close as 85 AU cannot be ruled out, a definitive experimental determination of the average TS location in the near future would place a firm additional constraint on the possible ranges of interstellar parameters.

We thank the staff at the International Space Science Institute (ISSI), where discussions leading to results of this publication were initiated, for their hospitality during our visit. This work was supported in part by the ISSI in Bern, INTAS grant 2001-0270, RFBR grants 01-02-17551 and 01-01-00759, NASA/Caltech grant NAG5-6912, and NASA/JPL contract 955460.

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