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Modeling of the outer heliosphere with the realistic solar cycle

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Abstract

Time-dependent kinetic-continuum model of the solar wind interaction with the two-component local interstellar cloud (LIC) has been developed recently [Izmodenov, V., Malama, Y.G., Ruderman, M.S. Solar cycle influence on the interaction of the solar wind with local interstellar cloud. Astron. Astrophys. 429, 1069–1080, 2005a.]. Here, we adopted this model to the realistic solar cycle, when the solar wind parameters at the Earth's orbit are taken from space data. This paper focuses on the results related to the termination shock (TS) excursion with the solar cycle that may help to understand Voyager 1 data obtained at and after the crossing of the termination shock and to predict the time of the TS crossing by Voyager 2.

Keywords: Heliospheric termination shock; Heliospheric interface; Solar wind; Solar cycle; Interstellar H atoms

1. Introduction

More than 30 years' (three solar cycles) observations of the solar wind show that its momentum flux varies by factor of ~2 from solar maximum to solar minimum. It has been shown theoretically that such variations of the solar wind momentum flux strongly influence the structure of the heliospheric interface, the region were the solar wind interacts with the interstellar gas. Recent review on the modeling of the heliospheric interface is given in Izmodenov and Baranov (2007).

Most models of the heliospheric interface, which take into account the solar cycle effects, ignored the interstellar H atom component or took this component into account by using simplified fluid or multi-fluid approximations. These implications were adopted because it is difficult to solve a 6D (time, two dimensions in space, and three dimensions in velocity-space) kinetic equation for the interstellar H atom component. Recently, the non-stationary, self-consistent model of the heliospheric interface was developed by Izmodenov et al. (2003a, 2005a), Izmodenov and Malama (2004a,b).

Izmodenov et al. (2005a) have studied the effects for the 'ideal' solar cycle. It was assumed that, at Earth's orbit, the solar wind number density oscillates harmonically, while the bulk velocity and temperature remain constant. The period of the harmonic oscillations was chosen to be 11 years.

The solution of the system of Euler equations for plasma, and the kinetic equation for interstellar H atoms was found numerically with the periodic boundary conditions for the solar wind at the Earth's orbit. The period of the solution is 11 years. The basic results for the plasma component are the following: (1) The solar cycle variation of the termination shock (TS) location is ±7 AU about its mean value. (2) The heliopause (HP) location varies by ±2 AU about its mean value. (3) The variation of the

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bow shock (BS) location is negligible. (4) There is a sequence of additional weak shocks and rarefaction waves in the region between the heliopause and the bow shock. The additional heat of the plasma in the outer helio-sheath induced by the shock waves is small and it is not observable in the calculations. (5) The numerical results in the region between the HP and BS are confirmed by an analytical solution based on the WKB approximation.

For the interstellar H atom component the following results were obtained: (1) The variation of the number density of the H atoms in the outer heliosphere is within 10%. The variation increases at 5 AU up to 30% due to strong ionization processes in the vicinity of the Sun. (2) The variations of the number densities of three populations of H atoms – primary and secondary interstellar atoms, and atoms created in the inner helio-sheath – are coherent in the entire supersonic solar wind region and determined by loss due to charge exchange. The coherent behavior of fluctuations disappear in the regions where the production process is dominant. (3) There is no significant variation of the temperature and bulk velocity of the primary and secondary interstellar H atoms with the solar cycle. However, the bulk velocity and kinetic temperature of atoms created in the inner helio-sheath vary with the solar cycle by 10–12%. It is shown that this variation reflects the plasma properties at the heliopause. (4) There is a qualitative difference between our results and the results obtained by using the fluid or multi-fluid description for the interstellar H atoms. It was shown that the multi-fluid description is less appropriate for the time-dependent case than for the stationary case because the Knudsen number is larger for the time-dependent problem.

In this paper, we present our first results of the time-dependent model of the solar wind interaction with the interstellar medium in the case of the realistic solar cycle, when the inner boundary conditions are based on the measurements of the solar wind parameters at 1 AU. This paper focuses on one specific aspect obtained in the frame of the global solution that is variation of the TS location toward Voyager 1 and Voyager 2 directions. This study may help to understand Voyager 1 data obtained at and after the crossing of the termination shock and to predict the time of the TS crossing by Voyager 2. Other results of our solutions (e.g., distributions of H atoms which are important to interpret backscattered solar Lyman α will be published elsewhere.

2. Model

2.1. Governing equations

The model considered here takes into account the solar wind α particles and ions of interstellar helium following Izmodenov et al. (2003b). Both heliospheric and interstellar magnetic fields are ignored in the model, despite their potential importance for the heliospheric interface structure (e.g., Izmodenov et al., 2005b; Izmodenov and Alexashov, 2006; Opher et al., 2006, 2007; Pogorelov and Zank, 2006; Pogorelov et al., 2006). The considered problem is axisymmetric. The system of non-stationary governing equations is the same as that solved by Izmodenov et al. (2005a). The plasma component is described by the hydrodynamics equations:

$$\frac{\partial\rho}{\partial t}+\nabla\cdot(\rho\mathbf{V})=q_1, \tag{1}$$

$$\frac{\partial(\rho\mathbf{V})}{\partial t}+\nabla\cdot\left(\rho\mathbf{V}\mathbf{V}+p\hat{I}\right)=\vec{q}_2, \tag{2}$$

$$\frac{\partial E}{\partial t}+\nabla\cdot[\mathbf{V}(E+p)]=q_3, \tag{3}$$

where $\rho=\rho_p+\rho_e+\rho_{He}$ is the total density of the ionized component, $p=p_p+p_e+p_{He}$ is the total pressure of the ionized component (Here, ρ_{He} denotes the He^+ density in the interstellar medium, and the He^{++} density in the solar wind), $E=\rho(\varepsilon+V^2/2)$ is the total energy per unit volume, $\varepsilon=p/(\gamma-1)\rho$ is the specific internal energy, and $\hat{I}$ is the unit tensor. The temperature of the plasma is determined from the equation of state $p=2(n_p+n_{He^+})kT$ for the interstellar plasma and $p=(2n_p+3n_{He^{++}})kT$ for the solar wind, where k is Boltzman's constant; n_p, n_{He^+} and $n_{He^{++}}$ are the proton, interstellar He ion and solar wind alpha particle number densities. In addition to the Eqs. (1)–(3), the continuity equations were solved for He^+ in the interstellar medium and for α-particles in the solar wind. Then the proton number density is calculated as $n_p=(\rho-m_{He}n_{He})/m_p$, where n_{He} denotes the He^+ number density in the interstellar medium, and the He^{++} number density in the solar wind. The source terms in the right hand sides of Eqs. (1)–(3) have the same expressions as for the stationary model (see, for example, Izmodenov et al., 2005a or Izmodenov and Baranov, 2007).

The system of Eqs. (1)–(3) is solved self-consistently together with the non-stationary kinetic equation for the velocity distribution function of the interstellar H atoms,

$$\begin{aligned}\frac{\partial f_H}{\partial t}+\mathbf{w}_H\cdot\frac{\partial f_H}{\partial\vec{r}}+\frac{\mathbf{F}_r+\mathbf{F}_g}{m_H}\cdot\frac{\partial f_H}{\partial\mathbf{w}_H}&=-\left(\nu_{ph}+\nu_{impact}\right)f_H(\vec{r},\mathbf{w}_H)\\&-f_H\cdot\int|\mathbf{w}_H-\mathbf{w}_p|\sigma_{ex}^{HP}f_p\left(\vec{r},\mathbf{w}_p\right)d\mathbf{w}_p\\&+f_p(\vec{r},\mathbf{w}_H)\int|\mathbf{w}_H^*-\mathbf{w}_H|\sigma_{ex}^{HP}f_H\left(\vec{r},\mathbf{w}_H^*\right)d\mathbf{w}_H^*.\end{aligned} \tag{4}$$

Here, $\mathbf{F}_r$ and $\mathbf{F}_g$ are the force of the solar radiation pressure and the gravitational force of the Sun, respectively; $f_p(\mathbf{r},\mathbf{w}_H)$ is the local Maxwellian distribution function of protons with gas-dynamic values $\rho(\mathbf{r})$, $\mathbf{V}(\mathbf{r})$ and $p(\mathbf{r})$; ν_{ph} is the photoionization rate; ν_{impact} is the electron impact ionization rate; σ_{ex}^{HP} is the effective cross-section of collisions connected with charge exchange, and $\mathbf{r}$ is the position vector.

2.2. Boundary conditions

At the Earth's orbit parameters of the solar wind – the proton and alpha particles number densities, the proton speed and temperature – are adopted from OMNIWeb of

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Goddard Space Physics Data Facilities at http://omniweb.gsfc.nasa.gov/ and from Web site of WIND-SWE Home Page maintained by the MIT Space Plasma Group. In our studies we used hourly data that is the highest resolution available at OMNIWeb. These hourly data were used to calculate fluxes of mass, momentum and energy. The fluxes with hourly resolution were used to calculate the fluxes averaged (over day and month). The averaged fluxes were then used to calculate averaged (over days and months) number densities, velocities and temperatures of the solar wind, which were used in our calculations as boundary conditions at 1 AU.

The described above procedure allows calculating averaged fluxes of mass, momentum and energy correctly. Another way to get averaged values is to calculate the daily/monthly averages directly from high resolution data. However, such averaging results in underestimation of the averaged momentum flux by 10% because $<a><b> \neq <ab>$. Our numerical experiments have shown that such overestimation of the momentum flux leads to displacement of the TS location by about 5 AU. The calculations with daily and monthly averaged fluxes give basically the same results.

In the model, we employed the OMNIWeb and Wind data for 22 years from 1984.5 to 2006.5 year. The momentum flux that was used in the calculations shown in Fig. 1a for 22 years and zoom for period from 2001 to 2007 in Fig. 1b. The results presented in this paper were obtained by using daily averaged values at 1 AU. However, our numerical experiments have shown that all results remain the same for monthly averaged values.

Our numerical grid is sufficient for modeling of the global structure of the heliospheric interface. The grid is not uniform and adaptive to the discontinuities by shock fitting procedure. However, it is rather coarse inside the TS to be able resolving small-scale structures. Inside the TS the grid has about 200 cells in radial direction. To verify whether such a grid is appropriate for current study or more cells are required we performed specific 1D numerical modeling of the non-stationary spherically symmetric solar wind. We performed the calculations from 1 AU to 100 AU for grids with 200, 1000, 10000 cells. The relevant for this paper conclusion of the 1D study is that the 200-cell grid does not allow to reproduce the fine structures in the solar wind density, speed and temperature profiles. However, it maps the general features in the radial profiles fairly well and can be useful in two- and three-dimensional calculations, which are considerably more time-expensive. Details of 1D study will be reported elsewhere.

For interstellar H atoms we took into account realistic time-dependent photoionization rate (Bzowski, 2001), and solar radiation pressure variations with time (Bzowski, 2001). The dependence of the solar radiation pressure on the radial velocity of the atom, $F_{\mathrm{rad}} = F_{\mathrm{rad}}(t, w_{\mathrm{H},r})$, is also taken into account. By doing this we assumed that F_{rad} is proportional to the ratio of the solar Ly α flux at wavelength corresponding to $w_{\mathrm{H},r}$ to the flux at the line center.

Interstellar boundary conditions were assumed as follows: $n_{\mathrm{p,LIC}} = 0.06\ \mathrm{cm}^{-3}$, $n_{\mathrm{H,LIC}} = 0.18\ \mathrm{cm}^{-3}$, $V_{\mathrm{LIC}} = 26.4$ km/s, $T_{\mathrm{LIC}} = 6500$ K, $n_{\mathrm{He,LIC}} = 0.015\ \mathrm{cm}^{-3}$. These values of interstellar velocity, temperature are close to those derived from the measurements of the interstellar helium (see, Möbius et al., 2004; Witte, 2004; Gloeckler et al., 2004; Lallement et al., 2004a,b). The values of $n_{\mathrm{p,LIC}}$, $n_{\mathrm{H,LIC}}$ were chosen in order to provide $n_{\mathrm{H,TS}} \sim 0.1\ \mathrm{cm}^{-3}$ as follows from Ulysses/SWICS pickup ion observations (Gloeckler and Geiss, 2004). Assuming the ratio H/He is equal to 10, the number density of the interstellar helium ions, $n_{\mathrm{He^+,LIC}}$, is $0.009\ \mathrm{cm}^{-3}$. Then we obtain that the ionization of interstellar helium is 0.375 which is in agreement with Wolff et al. (1999).

3. Results

The results of the model calculations are presented in Figs. 1 and 2. To show that our simulations are relevant to the prediction of the TS location in Voyager 1 and Voyager 2 directions we show (in Fig. 1c and d) comparison of the solar wind velocity, scaled proton number density ($n_{\mathrm{p}}R^2$, where R is the heliocentric distance in AU) calculated along the trajectory of *Voyager 2* (gray (green) curves) with actual *Voyager 2* observations.

In general, the calculated values are in rather good agreement with the measurements at *Voyager 2*. The exception is the period from 1995 till 1999. During this period the theoretical velocities and temperatures are lower, while the proton number densities are larger than observed (Fig. 1c and d). The reason of this significant discrepancy between the theory and the data is the following. The period from 1995 till 1999 corresponds to minimum of the solar activity when the current sheet was thin and *Voyager 2* was located in high-speed streams of the solar wind. Our calculations are based on Earth's orbit measurements of the solar wind that is inside the slow solar wind. Therefore, for this period the comparison is not valid and 3D model should be employed. For other periods *Voyager 2* was inside the slow solar wind that gives good agreement between the model and the data.

It is important to note fairly good agreement between the measured and calculated velocities after 1999. The heliospheric interface model predicts deceleration of the solar wind due to loss of its momentum caused by charge exchange with the interstellar H atoms (e.g., Baranov and Izmodenov, 2006). To explore this effect we performed additional numerical calculations of the solar wind evolution in the distant heliosphere for the case when charge exchange is ignored. The velocity calculated along the trajectory of *Voyager 2* is shown for this case in Fig. 1c as red (dashed) curve. It is seen that this curve lies above other curves. The effect of the solar wind slowdown due to charge exchange predicted by theoretical models is seen in the Voyager 2 data (black curve is Fig. 1c; see, also, Wang and Richardson, 2003). The good agreement of the theoret-

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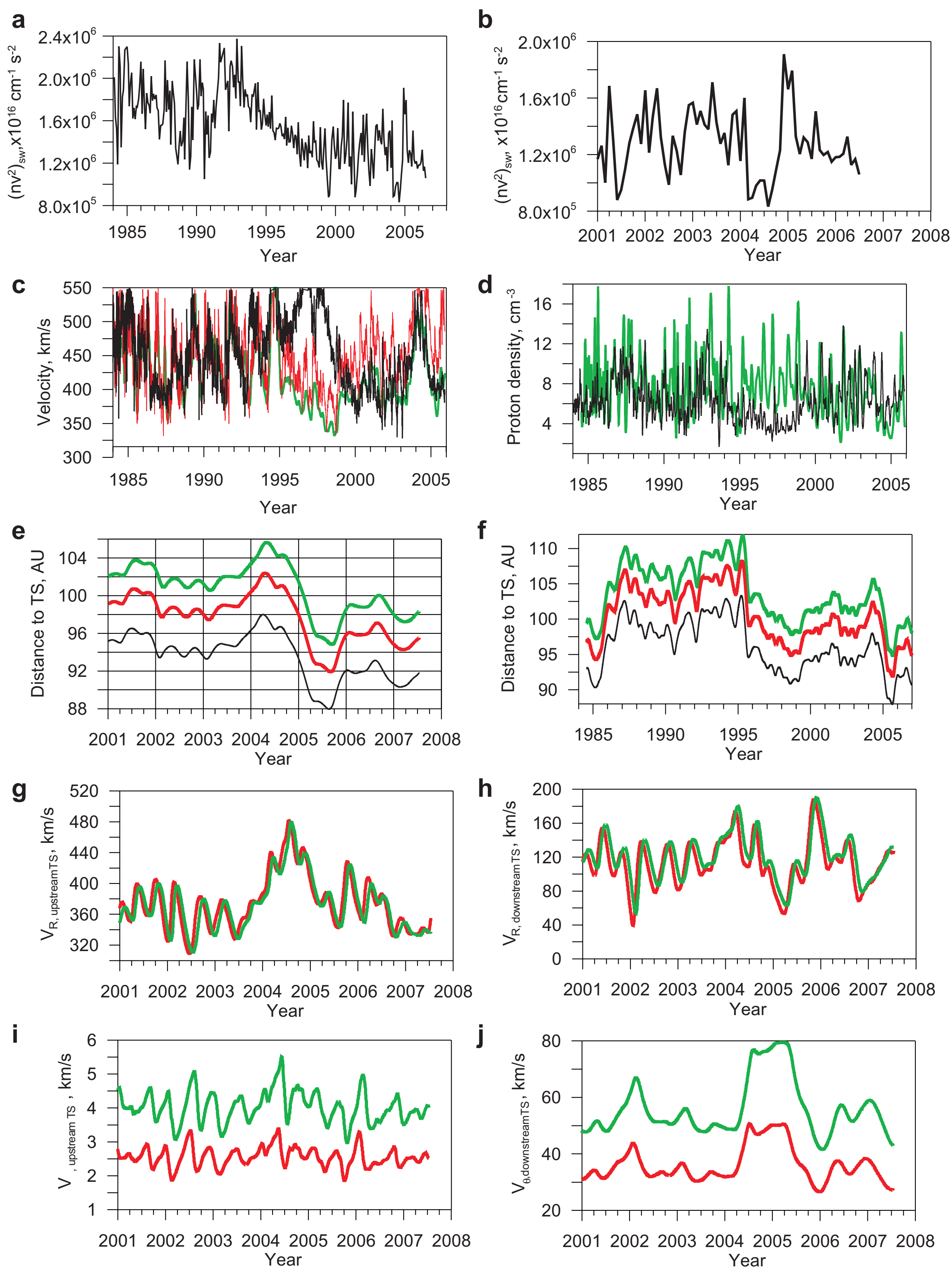

Fig. 1. (a and b) Monthly averages of the solar wind dynamic pressure at 1 AU. (c and d) Comparison of the solar wind number density and velocity calculated along the Voyager trajectory (green curves in color version or gray in b & w version of the paper). Red (dashed in b & w version) curves shows results of the model without charge exchange. (e and f) Distance to the TS in the upwind direction (black), in the directions of Voyager 1 (red) and Voyager 2 green). (g and h) Radial velocity of the solar wind upstream and downstream the TS in Voyager 1 (red) and Voyager 2 (green) directions. (i and j) Tangential velocity of the solar wind upstream and downstream the TS toward Voyager 1 (red) and Voyager 2 (green) directions. (For interpretation of the references in color in this figure legend, the reader is referred to the web version of this article.)

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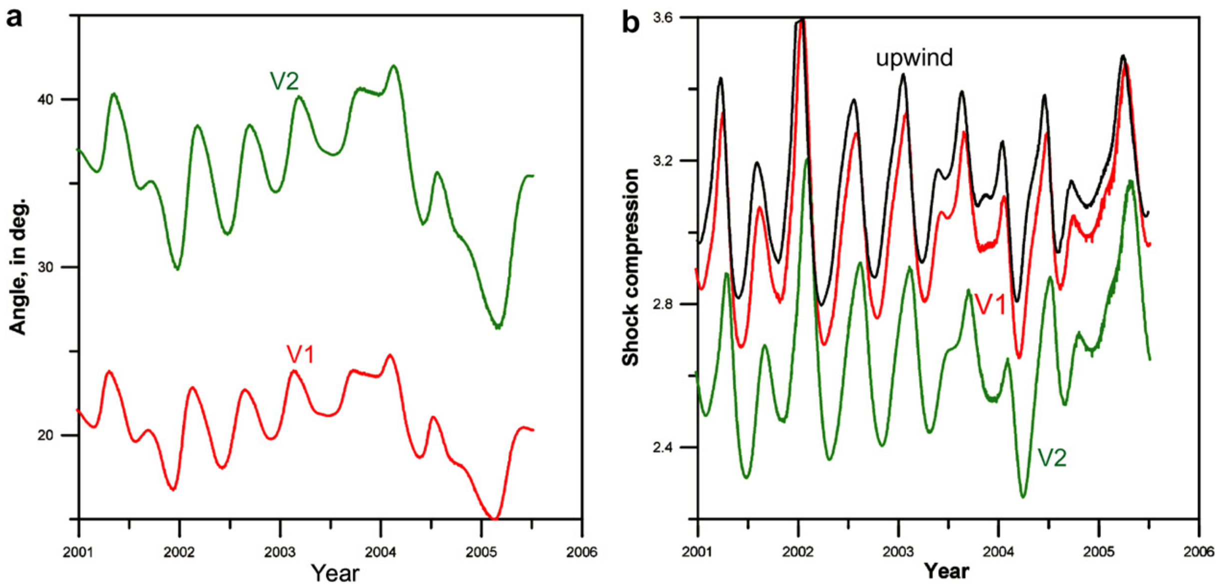

Fig. 2. (a) The angle between the normal to the termination shock and the solar wind velocity vector toward the Voyager 1 and Voyager 2 directions. (b) The compression of the TS as function of time calculated for the upwind direction and toward Voyager 1 and Voyager 2 directions.

ically predicted and measured velocities may serve as an addition validation of our model.

Fig. 1e and f show that, in upwind, the position of the TS fluctuates from ~88 AU to ~103 AU over the two last solar cycles. The TS fluctuates ±7.5 AU about the mean value of 95.5 AU. The fluctuations are not periodic as it was in the 'ideal' solar cycle (Izmodenov et al., 2005a). The position of the TS reflects the time-variations of the solar wind dynamic pressure at 1 AU shown in Fig. 1a and b. The delay in fluctuations of the TS as compared with the solar wind dynamic pressure fluctuations is about 1–1.2 year. For example, the minimum of the dynamic pressure in the middle of 2004 leads to the minimum of the distance to the TS in the middle of 2005. The rapid decrease of the dynamic pressure in the end of 2003–beginning of 2004 results in rapid motion of the TS toward the Sun one year later. Actually, the maximum inward speed of the termination shock occurs in the period Dec 2004–Jan 2005 that includes the period of the actual Voyager 1 crossing the termination shock. In the middle of December 2004 the inward speed of the TS was ~80 km/s.

Fig. 1e and f show the variation of the TS in Voyager 1 and Voyager 2 directions as well. It is seen that the distance to the TS in the direction toward Voyager 1 is at about 3 AU further than the distance in the upwind direction. In the direction of Voyager 2 the TS distance is further away by ~3 to 3.5 AU as compared with Voyager 1. The maxima and minima of the TS distance are slightly time-shifted toward Voyager 1 and Voyager 2 directions as compared with upwind. The time-shifts are within one and two months for Voyager 1 and 2, respectively.

Fig. 1g and h show the radial component of the solar wind velocity upstream and downstream the termination shock for the period from 2001 to 2007.5. The velocity varies significantly during 22 years from 320 km/s to 480 km/s. In December 2004 the radial component of velocity was about 400 km/s. The radial component after the shock crossing was rather small, 80 km/s. However, this value is significantly larger than the velocity inferred from Voyager/LECP observations (Decker et al., 2005). It is interesting to note that time-variations of the downwind radial velocity qualitatively look very similar to the velocity variations inferred from Voyager/LECP data. However, absolute values of Voyager/LECP velocities are always significantly smaller than the calculated velocities.

Fig. 1i shows the tangential components of the solar wind velocity in upwind termination shock toward Voyager 1 and Voyager 2 directions. It is seen that this component is within 3–6 km/s that demonstrates that the solar wind is almost radial upstream the shock. However, the tangential component of velocity increases significantly downstream the shock (Fig. 1j) when the radial component decreases. This shows that the TS is oblique in the direction of Voyager 1. It is even more oblique in the direction of Voyager 2. Fig. 2a shows the angle between the TS normal and the solar wind velocity vector upwind the TS. It is seen that toward Voyager 1 the angle varies around 20 degrees, while toward Voyager 2 the angle varies around 35°. The intensity of the shock, i.e., gas compression at the shock, varies with time too (Fig. 2b). The strongest compression is for the upwind direction. It fluctuates around 3 toward Voyager 1 direction, while toward Voyager 2 the averaged shock intensity is smaller and varies around 2.6.

4. Conclusions and discussion

We applied time-dependent kinetic-gas dynamic model (Izmodenov et al., 2005a) of the solar wind interaction with the two-component (plasma and H atoms) interstellar medium to study the effects of the realistic solar cycle. In this model the solar wind parameters at 1 AU from space experiments were used. In this paper, we focused on the results connected with the solar cycle fluctuations of the termination shock that can be useful for understanding and predicting Voyager 1 and 2 data. The results can be briefly summarized as follows:

- During the last two solar cycles the termination shock fluctuates by ±7.5 AU around its mean values of 95.5 AU.
- The fluctuations of the TS reflect the variations of the solar wind dynamic pressure at 1 AU with 1–1.2 year time-shift.
- For December 2004 the TS toward Voyager 1 direction is at 98 AU in the model that is 4 AU further as compared with actual TS crossing by Voyager 1.
- In December 2004 the TS moved toward the Sun with ~80 km/s.
- The angle between the normal to the termination shock and the solar wind velocity vector upwind the shock varies with the solar cycle around 20° in Voyager 1 direction and around 35° in Voyager 2 direction. The TS is oblique and tangential component of the solar wind velocity becomes significant, especially toward Voyager 2.

As it is seen above, the distance to the TS in Voyager 1 direction is 4 AU further in the model as compared with actual TS crossing by Voyager 1 in December 2004. Theoretically one can expect the termination shock closer to the Sun as compared with the model prediction. This is due to influence of additional pressure of the interstellar magnetic field (ISMF). Recent analysis of the backscattered solar Lyman α radiation by Lallement et al. (2005) has shown that the direction of interstellar H atom are ~4° shifted as compared with the direction of interstellar helium. Possibly this deflection of interstellar hydrogen is connected with the global asymmetry of the heliospheric interface due to influence of the interstellar magnetic field. Izmodenov et al. (2005b) have shown by using 3D kinetic-MHD model that the deflection can be reproduced in the model with ISMF of ~2.5 μG and its direction of 30–60° to upwind. Such ISMF would move the TS closer to the Sun by ~6–14 AU depending in the orientation of ISMF (Izmodenov and Alexashov, 2006). This would make the TS closer to the Sun as compared with actual distance.

The following modifications of the model could potentially resolve the problem and move the theoretically expected location of the TS toward its measured value:

1. Smaller ionization of interstellar hydrogen in the LIC. For example, for the model $n_{p,LIC} = 0.04\ cm^{-3}$, $n_{He,LIC} = 0.007\ cm^{-3}$ one can expect (e.g., see Izmodenov et al., 1999a) TS by 5–7 AU further from the Sun as compared with current model.
2. Multi-component treatment of the solar wind plasma (Malama et al., 2006) moves the TS ~5 AU away of the Sun.
3. After 2002 the dynamic pressure in the solar wind is larger in the realistic 3D solar wind as compared with the axisymmetric model considered here.
4. The heliospheric magnetic filed may play role (Opher et al., 2006; Pogorelov and Zank, 2006; Pogorelov et al., 2006).

All these modifications will be investigated in the future. Another possible modification is that the ISMF is differently oriented (Opher et al., 2007).

Our model predicts that in 2007 the TS is at 98 AU in the direction toward Voyager 2. This is still ~15 AU further as compared with the distance to the Voyager 2 spacecraft in 2007. According to the model we do not expect the crossing of the TS by Voyager 2 in 2007. Current model does not allow us to make prediction further since the solar wind parameters were restricted by the first half of 2006. If the solar wind dynamic pressure falls rapidly since that time then one can expect rather quick movement of the TS toward the Sun.

Finally, it is worthwhile to note that, in the first half of 2007 certain increase of the energetic particle fluxes is observed (see, e.g., Voyager/LECP data). Such an increase of the fluxes may indicate approaching the TS as it was with Voyager 1. If Voyager 2 crosses the TS in 2007–2008 this will mean that the heliosphere is strongly asymmetric, and interstellar and heliospheric magnetic field play even more important dynamic role than generally assumed.

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