Solar cycle heliospheric interface variations: influence of neutralized solar wind

N. A. Zaitsev[a] and V. V. Izmodenov[b*]

[a]Keldysh Institute of Applied Mathematics, Russian Academy of Sciences, zaitsev@spp.keldysh.ru

[b]Department of Aeromechanics and Gas Dynamics, Faculty of Mechanics and Mathematics, Lomonosov Moscow State University, izmod@ipmnet.ru

New non-stationary self-consistent model of the solar wind interaction with a two-component (atoms and plasma) local interstellar cloud is proposed. In this model the primary and secondary interstellar atoms are treated as quasi-stationary kinetic gas. Population of H atoms originated in the supersonic solar wind has is considered as zero-pressure fluid. Specific non-stationary effects introduced by the solar cycle fluctuations of the neutralized solar wind are explored.

1. Introduction

The solar wind (SW) interacts with the local interstellar cloud (LIC). The heliospheric interface is formed in this interaction. The structure of the interface and the interface plasma flow depend on the parameters of the SW and LIC and their variations with time. The LIC velocity with respect to the Sun ($V_{\rm LIC} \sim 26$ km s^{-1}) and the LIC temperature ($T_{\rm LIC} \sim 7000$ K) are reliably established. The sonic velocity, $a_{\rm LIC}$, corresponding to $T_{\rm LIC}$, is smaller than $V_{\rm LIC}$. Therefore, the interstellar flow is supersonic and the LIC Mach number, $M_{\rm LIC} = V_{\rm LIC}/a_{\rm LIC}$, is larger than unity. Therefore, the interstellar plasma flow is supersonic and two-shock plasma structure is formed in the LIC/SW interaction. Interstellar atoms, galactic and anomalous cosmic rays, interstellar and interplanetary magnetic fields may affect the interface. However, the basic features of the heliospheric plasma interface are the same: 1) the heliopause (HP) separates the SW plasma from interstellar plasma, 2) the termination shock (TS) decelerates, heats and compresses the solar wind plasma and 3) there is the pile-up plasma region - plasma wall - between the heliopause and the bow shock.

Interstellar H atom charge exchange with protons and significantly influence the heliospheric interface structure. The mean free path of H-atoms is compatible with the characteristic length of the problem considered. Therefore it is not correct to describe the

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H atom motion hydrodynamically ([1], [3]). The self-consistent axisymmetric model of the SW interaction with two-component (plasma and H atoms) LIC has been developed by Baranov and Malama [2]. A kinetic approach was used to describe H atoms in the model. However, the model does not take into account non-stationary processes in the SW.

Steinolfson [4] has numerically investigated the problem of the heliospheric interface response to 180 day period fluctuations in the solar wind ram pressure in the case of subsonic fully ionized interstellar gas. He found that the variation in the distance to the termination shock is only about 1 AU. Karmesin et al. [5] and Baranov and Zaitsev [6] studied the influence of the 11 year variation of the solar wind pressure onto the heliospheric interface with 2D hydrodynamic models. These authors concluded that the response of the position of the termination shock to the changes of the solar wind parameters is within 8 – 12% (or about 10 AU). The response of the heliopause is smaller and the response of the bow shock is negligible. Baranov and Zaitsev also pointed out that in the supersonic solar wind as well as in the heliosheath the plasma flow has a quasi-stationary behaviour, while in the pile-up region between the bow shock and the heliopause there is a sequence of shocks and rarefaction waves. However, the mean plasma distribution is close to the stationary plasma distribution.

In this work we investigate the effect of the solar cycle fluctuations of the fast solar neutrals flux onto the heliospheric interface. These energetic neutrals are created by charge exchange inside the heliopause and have significant influence on the compressed interstellar plasma (see, e.g., [3]).

2. Formulation of the Problem

The model [2] clearly shows, that there are four different types of H atoms in the heliospheric interface: i) the unperturbed interstellar neutral H atoms called Primary Interstellar Atoms or PIAs; ii) the compressed, decelerated, and Heated Interstellar Atoms (HIAs) formed by charge exchange with heated interstellar protons outside the heliopause; iii) the neutralized, decelerated, and Heated Solar Wind Atoms (HSWAs) formed in the heliosheath by charge exchange between the neutral interstellar gas and the hot protons of the decelerated and compressed solar wind, and iv) the neutralized Supersonic Solar Wind Atoms (SSWAs). These types of neutrals have different energy and spatial distributions in the interface. In Baranov-Malama model the influence of neutrals on plasma flow were taken into account as source terms Q in the right partxs of ithe Euler equations for plasma component.

To study properly the solar cycle influence on the heliospheric interface one should solve simultaneously the time-dependent Euler and Boltzmann equations. While the development of the corresponding Monte-Carlo algorithm is still in progress we would like to understand the basic physical effects of the solar cycle on the time-dependent interface from a simplified model. To study the influence of interstellar atoms we made the following assumptions:

1. Since the positions of the BS and the HP do not change significantly and fluctuations of plasma in this region are around stationary distributions, we assume that there is no influence of the solar cycle on the PIA's and HIA's. Hence the source terms Q_{PIA} and

Q_{HIA} into the plasma equations do not depend on the solar cycle and can be taken from the stationary solution.

2. We neglect the changes of HSWA's over the solar cycle.

3. For the number densities n_{PIA} and n_{HIA} we assume that

$$n_H = exp\left\{-\frac{\sigma_{ex} n_E V_E r_E^2}{r V_{H,TS}}\right\} n_{H,TS},$$

where σ_{ex} is the charge exchange cross esctionr; n_E, V_E are the solar wind proton number density and temperature, respectively; $n_{H,TS}$ $V_{H,TS}$ the number densitrnd velocity of interstellar atoms at the termination shock, r is the heliocentric distance, r_E=1 AU is the distance to the Earth. This formula is the zero order approximation of interstellar neutral distributions in the interface, but for our objectives it is sufficient.

4. We assume that SSWA's can be treated as a zero-pressure fluid. The governing equations for this fluid are mass and momentum conservation lawis under the condition that the pressure $P_{SSWA} = 0$. The mutual influence of H-atoms and the plasma flow is modelled by the corresponding source terms in the mass conservation law and the momentum conservation law. In the stationary case this model gives the distribution of the SSWA's number density close to that obtained with the Monte-Carlo simulation.

In order to simulate the 11-year solar cycle we changed the plasma velocity at the Earth orbit according to a sinusoidal law so that the ram pressure was varied by a factor of two. The sinusoidal variation of V_E is the first harmonic of the real time dependence of the SW parameters.

3. Numerical results

Numerical results discussed below were obtained on the basis of a statinary solution computed for the following parameters [7]: $n_{p\infty} = 0.07\ cm^{-3}$, $n_{H\infty} = 0.2\ cm^{-3}$, $V_\infty = 25\ km/s$, $T_\infty = 5672$K, $n_{E0} = 7\ cm^{-3}$, $V_{E0} = 450\ km/s$, $T_{E0} = 73507$K.

Our calculations show that the qualitative features of the non-stationary LIC – SW interaction established in [6] take place in the presence of neutral H-atoms as well. But the effect of the solar activity cycle is quantitatively stronger because the interface is closer to the Sun. For example, the TS excursion during the solar cycle on the axis of symmetry is about 30 AU, i.e. about 30% of its mean solar distance.

Figure 1 shows the farthest and the nearest discontinuities positions in the upwind hemisphere parameters (solid lines). In the same figure the steady state positions of the BS, HP and TS are shown (by circles). One can see that the region between the BS and HP becomes wider: the mean location of the BS is farther from the Sun and the mean location of the HP is closer to the Sun than the corresponding steady state positions.

The mean distributions of the plasma number density on the axis of symmetry in the region between the BS and HP is shown in Figure 2. The stationary distribution of the plasma number density in the same region is also shown. One can see that the mean density in the non-stationary cases is much less than in the stationary solution. This phenomenon can significantly influence the penetration of neutral H-atoms into the solar system.

Figure 2 also shows the presense of a sequence of shocks and rarefaction waves moving from the HP to the BS similar to the one obtained in [6].

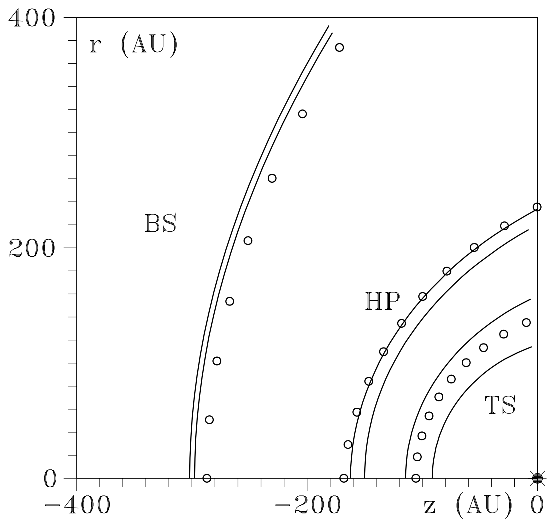

Figure 1. The geometrical pattern of the discontinuities: solid lines — minimum and maximum heliocentric distances, circles — the stationary position of the TS.

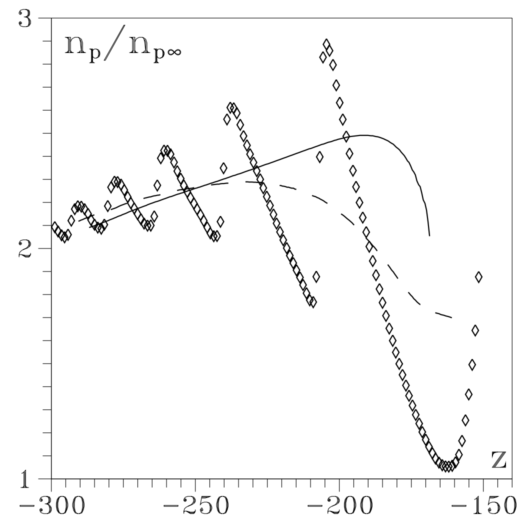

Figure 2. The interstellar plasma density: stationary solution (solid line), non-stationary solution (diamonds) and the mean density distribution (dashed line).

4. Conclusions

The conclusions of presented study can be summarized as following:

1. The solar cycle influence on the variation of the termination shock is stronger in the case with H atoms than it would be in the case without H atom component.

2 Due to the solar cycle variations of the neutralized solar wind, i.e. atoms created in the supersonic solar wind by charge exchange with solar wind protons, the region between the heliopause and the bow shock become wider and mean plasma density in the region become smaller than for the stationary problem. This can be important for interpretations of heliospheric absorption in Ly-α.

REFERENCES

1. Baranov, V. B., V. V. Izmodenov, and Y. G. Malama, *J. Geophys. Res.*, IDS, 9575-9585, 1998.
2. Baranov, V. B., and Y. G. Malama, *J. Geophys. Res.*, **98**, 15157-15163, 1993.
3. Izmodenov, V. V., this issue.
4. Steinolfson, R. S., *J. Geophys. Res.*, **99**, no. 7, pp. 13307-13314, 1994.
5. Karmesin, S. R., Liewer, P. C. and Brackbill, J. U. *Geophys. Res. Lett.*, **vol. 22**, no. 9, pp. 1153 – 1156, 1995.
6. Baranov, V. B. and Zaitsev, N. A. *Geophys. Res. Lett.*, **Vol. 25**, No. 21, pp. 4051 – 4054, 1998.
7. Izmodenov V. V., J. Geiss, R. Lallement, et al., J. Geophys. Res. 104, 4731,1999a.