JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 105, NO. A3, PAGES 5167–5177, MARCH 1, 2000

Self-consistent model of the solar wind interaction with three-component circumsolar interstellar cloud: Mutual influence of thermal plasma, galactic cosmic rays, and H atoms

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Abstract. In this paper we continue our study of the galactic cosmic ray (GCR) influence on the structure of the heliospheric interface plasma flow [*Myasnikov et al.*, this issue]. The model presented here is more realistic and takes the mutual influence of plasma, neutral, and cosmic ray components into account self-consistently. In the model, GCRs are described hydrodynamically under the assumption that their mass density is negligible; while neutrals are described kinetically. We explore the GCR influence on the heliospheric interface plasma structure by varying the diffusion coefficient, cosmic ray pressure, and adiabatic index. The problem is studied numerically, using the global iterations that couple the soft fitting technique for describing the plasma and GCR components and Monte Carlo simulations for H atoms. A strong GCR modulation is found in the heliospheric interface. At the same time, the GCR influence on the plasma flow is negligible as compared with the influence of H atoms. The exception is the bow shock, a structure which can be strongly modified by the cosmic rays. The Baranov–Malama model is therefore acceptable for interpretation of the physical processes in the heliosphere as long as the processes are not related to the bow shock structure. Although the simplest model of the cosmic ray transport is good enough to estimate GCR influence on the plasma and atom distributions in the heliospheric interface, more advanced models should be used to interpret the observed GCR spectra.

1. Introduction

At present, there is a growing interest in the studies of the solar wind (SW) interaction with the local interstellar cloud (LIC). Development of complicated theoretical models, which became possible due to a widespread penetration of computational hydrodynamics into space physics, is accompanied by new high-quality observations on spacecraft. It is currently believed that LIC consists of at least four components (plasma, neutrals, magnetic field, and galactic cosmic rays) [e.g., *Holzer*, 1989]. The mutual influence of these components should be taken into account in the theoretical models of the SW–LIC interaction. From a theoretical point of view, the study of such multicomponent flow is quite complicated, partly because of the need for a kinetic description of interstellar atoms [*Baranov et al.*, 1998]. Besides, the uncertainty in some LIC parameters forces a theoretician to carry out a parametric study of any particular physical effect. Thus the most effective way to develop a theoretical model is a step-by-step incorporation of new physical processes, whose influence on the heliospheric interface is expected to be pronounced and, therefore, important for interpretation of spacecraft observations.

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Paper number 1999JA000166.
0148-0227/00/1999JA000166$09.00

The first self-consistent model of the SW interaction with two-component (plasma and H atoms) LIC has been suggested by *Baranov et al.* [1991] and developed by *Baranov and Malama* [1993, 1995, 1996] and *Baranov et al.* [1998]. Using this two-shock heliospheric interface model (hereafter the Baranov-Malama model), *Izmodenov et al.* [1999a] have recently attempted to reconcile the Solar Wind Ion Composition Spectrometer (SWICS) Ulysses pickup ion data, Ly α measurements, and low-frequencies radio emissions, and derived some important parameters of LIC. However, the Baranov–Malama model does not take into account the influence of cosmic rays, magnetic fields, spatial, or nonstationary effects in the undisturbed SW and other effects. At the same time, some of these effects may significantly influence the heliospheric interface structure and affect any conclusion about the undisturbed LIC parameters. For example, our first attempt to consider the influence of galactic cosmic rays (GCRs) on the heliospheric interface structure [*Myasnikov et al.*, this issue] (paper 1 or companion paper hereafter) confirmed the above statement. In the companion paper we have studied the mutual influence of plasma and cosmic ray components and constructed a self-consistent model of the solar wind interaction with a two-component (plasma and galactic cosmic rays) interstellar medium. It has been found that there is significant modification of the heliospheric interface structure by GCRs for small and moderate values of the cosmic ray diffusion coefficient. To clarify the effect of plasma - GCR coupling, we have neglected the influence of interstellar atoms in paper 1. At the same time the preliminary estimations [*Izmodenov*, 1997] show that the GCR influence can be significant only at the discontinuities if neutrals are taken into account. Thus the neutrals may decrease the strong GCR influence on the plasma structure.

In the present paper we study the mutual influence of thermal plasma, GCRs, and interstellar atoms, and develop a model of the solar wind interaction with a three-component (plasma, H atoms, and GCRs) interstellar medium. To describe plasma and GCRs, we use the same physical model and numerical technique as in paper 1. The flow of interstellar neutrals is described kinetically as in the Baranov-Malama model.

The structure of the paper is the following. In section 2 we briefly describe our model. In section 3 we present results of the simulations which demonstrate the mutual influence of GCRs and neutrals, as well as their influence on the plasma flow. We discuss these results in section 4 and draw our conclusions in section 5.

2. Model

As in paper 1, let us consider a two-dimensional (2-D) axisymmetric model of the SW/LIC interaction. The interstellar plasma component and GCRs are treated as a two–fluid mixture. GCRs are considered as a hot gas of negligible mass density but nonneglígible energy density. To describe the flow of interstellar atoms we solve the Boltzmann equation:

$$\begin{aligned} \mathbf{w}_{\mathrm{H}} \cdot \frac{\partial f_{\mathrm{H}}(\mathbf{r}, \mathbf{w}_{\mathrm{H}})}{\partial \mathbf{r}} + \frac{\mathbf{F}}{m_{\mathrm{H}}} \cdot \frac{\partial f_{\mathrm{H}}(\mathbf{r}, \mathbf{w}_{\mathrm{H}})}{\partial \mathbf{w}_{\mathrm{H}}} = \\ -f_{\mathrm{H}}(\mathbf{r}, \mathbf{w}_{\mathrm{H}}) \int |\mathbf{w}_{\mathrm{H}} - \mathbf{w}_p| \sigma_{ex}^{\mathrm{HP}} f_p(\mathbf{r}, \mathbf{w}_p) d\mathbf{w}_p \\ + f_p(\mathbf{r}, \mathbf{w}_{\mathrm{H}}) \int |\mathbf{w}_{\mathrm{H}}^* - \mathbf{w}_{\mathrm{H}}| \sigma_{ex}^{\mathrm{HP}} f_{\mathrm{H}}(\mathbf{r}, \mathbf{w}_{\mathrm{H}}^*) d\mathbf{w}_{\mathrm{H}}^* \\ -(\beta_i + \beta_{\mathrm{impact}}) f_{\mathrm{H}}(\mathbf{r}, \mathbf{w}_{\mathrm{H}}). \end{aligned} \qquad (1)$$

Here $f_{\mathrm{H}}(\mathbf{r}, \mathbf{w}_{\mathrm{H}})$ is the distribution function of H atoms; $f_p(\mathbf{r}, \mathbf{w}_p)$ is the local distribution function of protons, assumed to be Maxwellian; $\mathbf{w}_p$ and $\mathbf{w}_{\mathrm{H}}$ are the individual proton and H atom velocities, respectively; $\sigma_{ex}^{\mathrm{HP}}$ is the charge exchange cross section of a H atom with a proton; β_i is the photoionization rate; m_{H} is the atomic mass; β_{impact} is the electron impact ionization rate; and $\mathbf{F}$ is the sum of the solar gravitational force and the solar radiation pressure force.

The plasma and neutral components interact mainly by charge exchange. However, photoionization, electron impact ionization, solar gravitation, and radiation pressure are also taken into account in equation (1). The interaction of the plasma and neutral components leads to the mutual exchange of mass, momentum and energy. A source term $Q = \{q_1, q_{2,z}, q_{2,r}, q_3, 0\}^T$ should be added to the right-hand side of the plasma equations (see equation (1) in paper 1). The terms $q_1, q_2 = \{q_{2,z}, q_{2,r}\}$, q_3 describe the mass, momentum, and energy sources in the thermal plasma component due to interaction with neutrals. They can be expressed through the integrals of the atom distribution function f_{H}:

$$q_1 = n_{\mathrm{H}} \cdot (\beta_i + \beta_{impact}), n_{\mathrm{H}} = \int f_{\mathrm{H}}(\mathbf{w}_{\mathrm{H}}) d\mathbf{w}_{\mathrm{H}},$$

$$q_2 = n_{\mathrm{H}} \cdot \int (\beta_i + \beta_{impact}) \mathbf{w}_{\mathrm{H}} f_{\mathrm{H}}(\mathbf{w}_{\mathrm{H}}) d\mathbf{w}_{\mathrm{H}} +$$
$$n_{\mathrm{H}} \cdot \int \int \beta_{ex} (\mathbf{w}_{\mathrm{H}} - \mathbf{w}_p) f_{\mathrm{H}}(\mathbf{w}_{\mathrm{H}}) f_p(\mathbf{w}_p) d\mathbf{w}_{\mathrm{H}} d\mathbf{w}_p,$$

$$q_3 = n_{\mathrm{H}} \cdot \int (\beta_i + \beta_{impact}) \frac{\mathbf{w}_{\mathrm{H}}^2}{2} f_{\mathrm{H}}(\mathbf{w}_{\mathrm{H}}) d\mathbf{w}_{\mathrm{H}} +$$
$$n_{\mathrm{H}} \cdot \int \int \beta_{ex} \frac{1}{2} (\mathbf{w}_{\mathrm{H}}^2 - \mathbf{w}_p^2) f_{\mathrm{H}}(\mathbf{w}_{\mathrm{H}}) f_p(\mathbf{w}_p) d\mathbf{w}_{\mathrm{H}} d\mathbf{w}_p.$$

Here $\beta_{ex} = n_p \int u \sigma_{ex}^{HP}(u) f_p(\mathbf{w}_p) d\mathbf{w}_p$ is the charge exchange rate, and u is the relative atom-proton velocity.

All physical and numerical boundary conditions for the plasma component and GCRs are taken to be the same as in paper 1. In the undisturbed interstellar medium the distribution function f_{H} is assumed to be Maxwellian.

In general, a schematic structure of the flow under consideration is expected to be similar to that described by the Baranov-Malama model. Namely, the collision of the supersonic SW with the flow of the LIC plasma component results in formation of a complex interaction region which includes the termination shock (TS), contact discontinuity (or, heliopause, HP) and bow shock (BS) (Figure 1). Owing to the influence of H atoms the TS becomes more spherical, and the Mach-type reflection from the symmetry axis disappears [*Baranov and Malama*, 1993]. Since GCRs make the termination shock more spherical as well (paper 1), we do not expect a triple point here. As in the case with $Q = 0$, GCRs may drastically modify the structure of the shocks, which may be split on the precursor and subshock or may be pure diffusive (see section 3 in paper 1).

In order to carry out numerical calculations in the frame of the hybrid (kinetic and gasdynamic) model, the global iterations suggested by *Baranov et al.* [1991] and developed by *Baranov and Malama* [1993, 1995] were applied. At the first iteration, distributions of the plasma and GCR parameters resulting from solution of equations (1) in paper 1 with $Q = 0$ are found. As in paper 1, this is done using the soft fitting technique [*Myasnikov et al.*, 1997; paper 1]. Since the technique allows us to approximately fit discontinuities, the Monte Carlo method with splitting of trajectories [Malama, 1991] can be directly applied. Then the term Q is calculated and used thereafter to find plasma and GCR distributions at the next iteration. The new plasma distributions are, in turn, the base for the next Monte Carlo simulation of H atom trajectories and for the calculation of new source terms. The iterative process continues until the plasma, cosmic ray, and neutral atom distributions are essentially independent of the iteration number.

3. Results

To solve the problem formulated above, let us adopt the value 0.2 cm^{-3} for the interstellar H atom number density. This value has been deduced by *Gloeckler et al.* [1997], who used new SWICS pickup results and the interstellar HI/HeI ratio of 13 ± 1 (the average ratio toward the nearby white dwarfs). Following paper 1, the parameters of the undisturbed plasma component of the solar wind and LIC are taken as $n_{p,E} = 7$ cm^{-3}, $V_E = 450$ km s^{-1}, $T_E = 73,600$ K, $n_{p,\mathrm{LIC}} = 0.07$ cm^{-3}, $V_{\mathrm{LIC}} = 25$ km s^{-1}, and $T_{\mathrm{LIC}} = 5680$ K. Here $n_{p,\mathrm{LIC}}$ and $n_{p,E}$ are the proton number densities in the undisturbed LIC and at the Earth's orbit, respectively, V_{LIC} and V_E are the bulk velocities, and T_{LIC} and T_E are the plasma temperatures. At first, we also fix both the plasma and GCRs adiabatic indexes as 5/3, and the value of the interstellar cosmic ray pressure $p_{c,\mathrm{LIC}} = 0.18$ eV cm^{-3}. For the energy-averaged diffusion coefficient k we adopt two values, 3.75×10^{21} cm^2 s^{-1} and 3.75×10^{22} cm^2 s^{-1}.

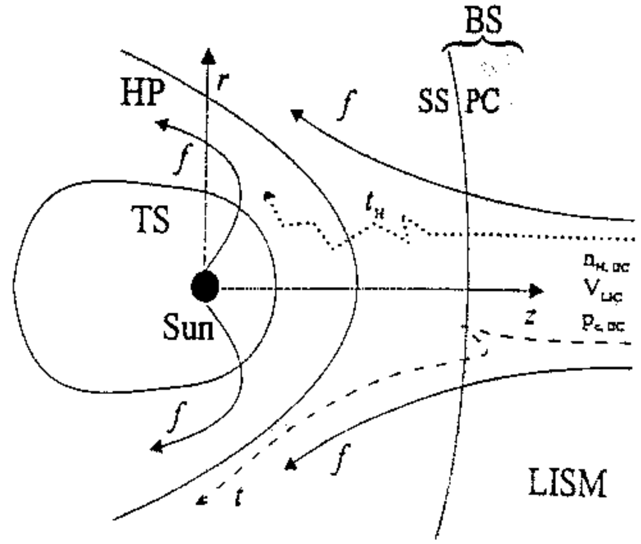

Figure 1. A schematic diagram of the solar wind (SW) interaction with three-component local interstellar cloud (LIC). TS denotes the termination shock; HP denotes the contact discontinuity (heliopause); BS denotes the bow shock, which can be split into the subshock (SS) and precursor (PC); f denotes plasma streamlines; and t and t_H denote some of possible trajectories of cosmic ray particles and H atoms, respectively. LISM denotes the local interstellar medium.

It can be argued that the average value of the diffusion coefficient in the galactic disk is several orders of magnitude higher than the values above. However, the Sun is located in a very specific place of the interstellar medium called the local interstellar cloud (LIC). It is presently well known that LIC is not in the ionization balance [e.g. *Lallement*, 1996]. At the same time there is no observational evidence on the direction and magnitude of the local interstellar magnetic field, nor its turbulence level. Thus, the diffusion coefficient k can still be considered as a free parameter in the theoretical study.

The reason for choosing small values of the diffusion coefficient here comes from the results of the parametric study presented in paper 1. It has been shown, albeit for $n_{\mathrm{H,LIC}} = 0$, that it is those values of the diffusion coefficient that yield the most pronounced effect. The GCR pressure leads to a shift of the TS and HP toward the Sun, when compared with the pure gasdynamical case (cf. dotted and dashed lines in Figure 2a). Both the TS and BS are pure diffusive (see Figure 3a of Paper 1). Moreover, the termination of the solar wind is accompanied by the appearance of an additional shock, which is located between the TS and HP. The additional shock is shown in Figure 3a of paper 1, and a discussion concerning the nature of the additional shock is given in section 3 of this paper. It has been shown in paper 1 that for diffusion coefficients $k > 4 \times 10^{22}$ cm^2 s^{-1} the effect of GCRs on the interface structure is negligibly small. Since we expect that interstellar atoms reduce the influence of GCRs on the plasma structure

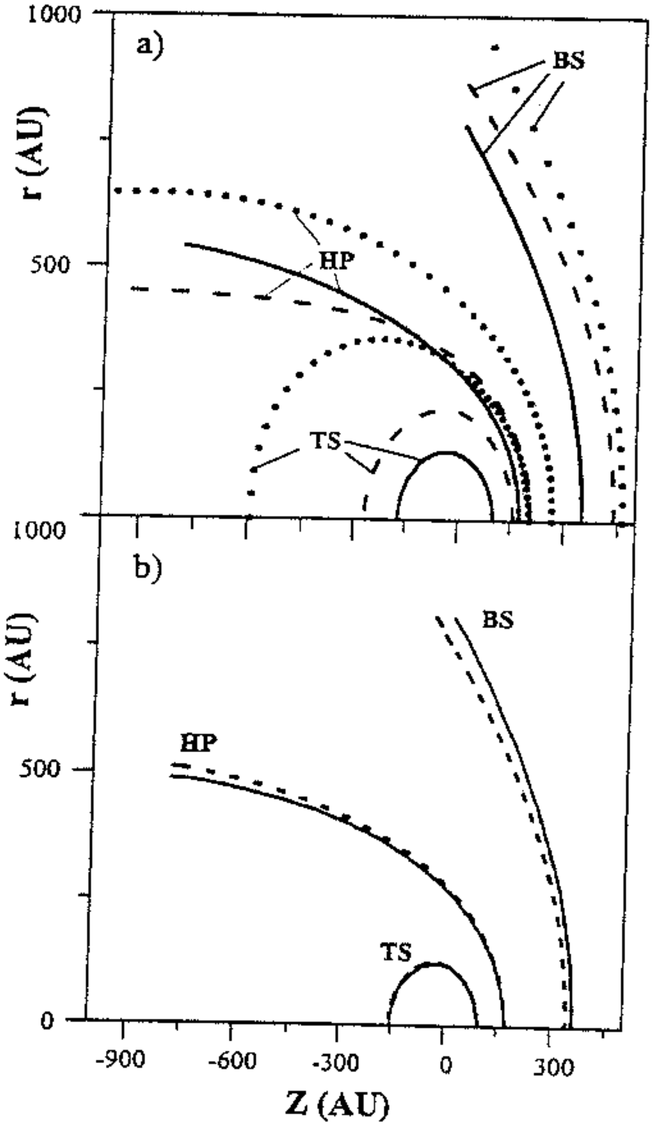

Figure 2. Geometrical structure of the SW/LIC interaction region for different sets of the flow and model parameters. (a) Dotted lines show the discontinuities in pure gasdynamical case, dashed lines show the case of the SW interacting with two-component (plasma and GCRs) LIC (diffusion coefficient $k = 3.75 \times 10^{21}$ cm^2 s^{-1}), and solid lines show another two-component case of LIC with plasma and atoms. (b) The cases of three-component model. Dashed lines present the case for diffusion coefficient $k = 3.75 \times 10^{21}$ cm^2 s^{-1}, and solid curves present the case for diffusion coefficient $k = 3.75 \times 10^{22}$ cm^2 s^{-1}.

[*Izmodenov*, 1997], there is no reason to perform calculations with diffusion coefficients larger than 4×10^{22} cm^2 s^{-1}.

Figure 2a demonstrates also the influence of H atoms on the flow pattern geometry (solid lines) when GCRs are not taken into account. One can see that the influence of neutrals and galactic cosmic rays on the shapes and positions of the discontinuities are similar. Namely, the neutrals push the shocks and the heliopause toward the Sun as well (dashed and solid lines in Figure 2a). The effect is, however, stronger for neutrals since for the chosen set of parameters the additional pressure contributed by interstellar atoms is larger than the pressure contributed by GCRs. This fact permits us to expect that the influence of GCRs on the plasma flow will not be strongly pronounced if neutrals are taken into account.

Our calculations, in general, confirm this statement. Figure 2b shows the geometrical pattern for the three-component model and two different values of the diffusion coefficient $k = 3.75 \times 10^{21}$ cm^2 s^{-1} (dashed lines) and $k = 3.75 \times 10^{22}$ cm^2 s^{-1} (solid lines). The shapes and positions of the shocks and the heliopause are very close to the results of the two-component (plasma and neutrals) model (solid lines in Figure 2a). The influence of GCRs manifests itself in the shape and position of the termination shock. The shock moves toward the Sun from 170 AU to 150 AU in the downwind direction. At the same time, the shift of the TS in the upwind direction is less than 5 AU. Thus the TS becomes more spherical.

Another effect of GCRs on the plasma flow is demonstrated in Figure 3. The plasma density distributions are shown for several sets of parameters in the upwind direction. Although GCRs have no effect on the position of the BS, the shock structure is considerably modified for $k = 3.75 \times 10^{21}$ cm^2 s^{-1} (dashed line). In this case the BS has a pure diffusive structure as in the two-fluid (plasma and GCRs) model. This diffusive structure of the BS disappears for the larger diffusion coefficient $k = 3.75 \times 10^{22}$ cm^2 s^{-1} (solid line), and the plasma density distribution is practically the same as without GCRs. The diffusive nature of the TS in the upwind (for $k = 3.75 \times 10^{21}$ cm^2 s^{-1}) and downwind (for $k = 3.75 \times 10^{22}$ cm^2 s^{-1}) directions, which has been discussed in paper 1 (see Figure 3a of paper 1), disappears when atoms are taken into account. There is no precursor region in this case.

Let us consider now the influence of GCRs on the interstellar atoms in the heliospheric interface. Using the Monte Carlo technique with splitting of trajectories, we may distinguish several populations of interstellar neutrals in the heliosphere. These populations have different properties and, therefore, different observational consequences.

Our calculations show that the original (primary) interstellar H atoms do not experience any influence of GCRs, especially in the regions close to the Sun where the interstellar atoms are measured as pickup ions or indirectly through solar backscattered Ly α radiation. The same is true for the "supersonic solar wind" atoms. These atoms are formed in the supersonic solar wind by charge exchange of the interstellar neutrals with SW protons. It is those atoms that disturb the interstellar plasma in front of the BS.

In contrast, for the compressed, decelerated, and heated interstellar atoms (HIAs) formed by charge ex-

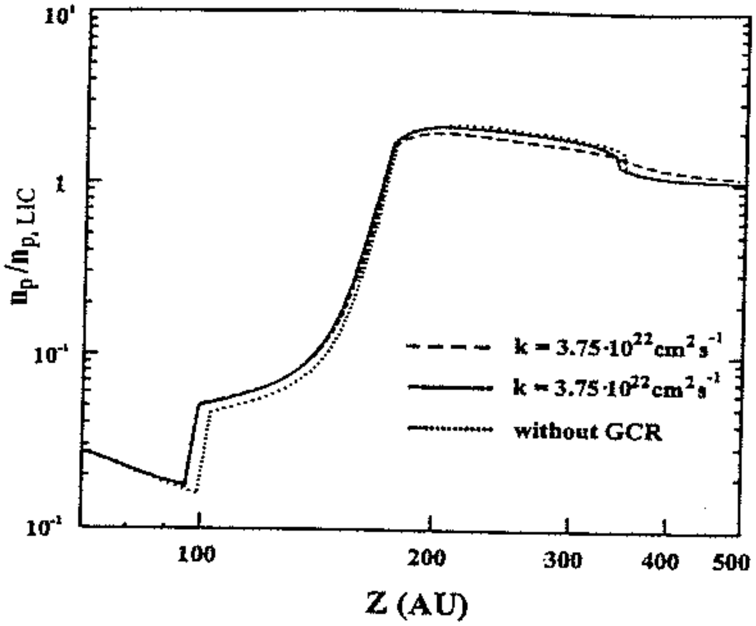

Figure 3. The distribution of the plasma density in the upwind direction. Two-component case with interstellar atoms and plasma is presented by dotted line, three-component cases are shown for two different diffusion coefficients $k = 3.75 \times 10^{21}$ cm^2 s^{-1} (dashed line) and $k = 3.75 \times 10^{22}$ cm^2 s^{-1} (solid line).

change with heated interstellar protons outside the HP, the influence of GCRs is more noticeable. The HIAs on the upwind side of the heliosphere (i.e., the direction from which the interstellar wind flows) collectively make up the so-called hydrogen wall. This hydrogen wall has been theoretically predicted by *Baranov et al.* [1991] and detected by *Linsky and Wood* [1996]. As was mentioned above, the incorporation of GCRs results in weakening of the BS. This, in turn, leads to a decrease of the hydrogen wall (Figure 4a). Nevertheless, the interstellar atom density increases in front of the hydrogen wall due to the smooth diffusive structure of the BS. Thus, in spite of smaller density in the hydrogen wall, the H atom column density along the line of sight is approximately the same for the two cases considered. The same is true for other directions. Thus GCRs do not influence the Ly α absorption by HIAs. Just as with primary interstellar atoms, we do not see any influence of GCRs on HIA distributions inside the TS.

Finally, 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 could produce extra absorption at positive red shifts observed in the Ly α line with the Goddard High Resolution Spectrograph (GHRS) on the Hubble Space Telescope (HST) [*Izmodenov et al.*, 1999b]. Therefore it is important to know the effect of GCRs on this atom population. It is seen in Figure 4b that without GCRs the atom density increases in the region between the TS and HP as compared with the three-component model. The effect, however, is not strong since the geometrical size of the heliosheath does not significantly depend on GCRs. Thus GCRs have a small influence on HSWAs as well.

At the same time the GCR distribution is very sensitive to the chosen interface model. Figure 5 presents the GCR pressure distribution along the axis of symmetry in the upwind direction for the two-fluid (plasma and GCRs) model (dotted line) and for the three-component model (solid and dashed lines). The maximum of the GCR pressure is much lower with neutrals than in the calculations without them. The maximum is located at the additional shock if there are no neutrals (dotted line). Then it shifts to the vicinity of the BS when atoms are taken into account (dashed line). To explain the effects, recall that there are three physical processes influencing the GCR pressure distribution in the heliospheric interface. They are convection by the plasma flow, spatial diffusion, and particle acceleration in the regions where the flow is compressed, in particular, at the BS, HP, and TS (paper 1). The convection and acceleration tend to increase the GCR pressure and create maxima, while the diffusion smooths them and may change their locations. For the moderate diffusion coefficients, such as $k \approx 10^{21}$ cm^2 s^{-1}, the maximum of the cosmic ray pressure near the additional shock is caused by strong acceleration of GCRs at the TS, additional shock, and, probably, HP. Indeed, for lower values of the diffusion coefficient, GCRs can not overcome the plasma counterflow in the region between the TS and HP to reach the TS (see paper 1). At large values of the diffusion coefficient, acceleration at the TS is not efficient either, since the diffusion length of cosmic rays in

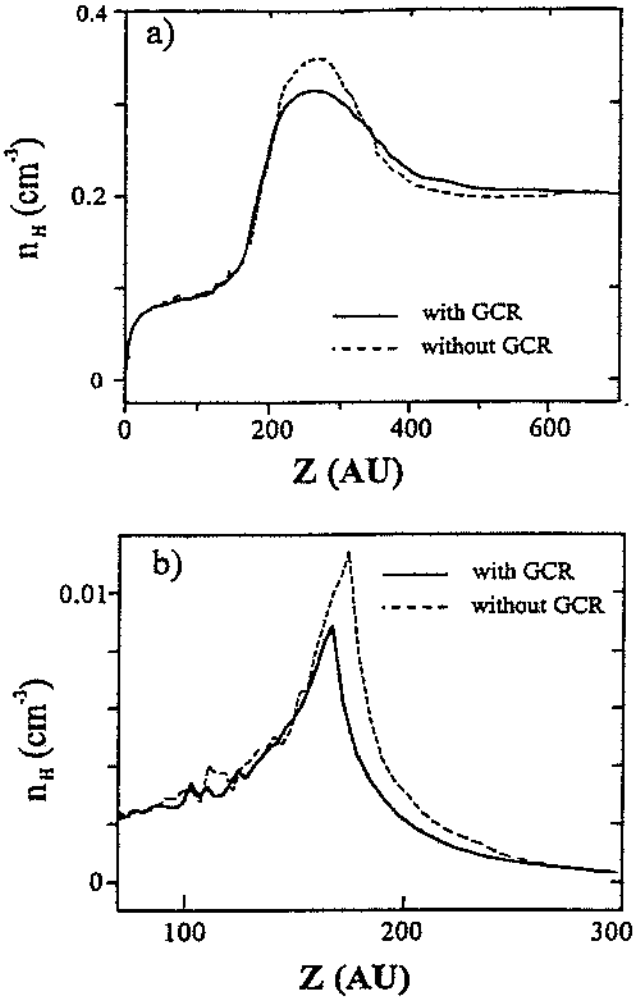

Figure 4. Number density of (a) interstellar atoms and (b) "heated solar wind" atoms (HSWAs) in the upwind direction are presented for the two-component (dashed lines) and three-component (solid lines) models of LIC. The diffusion coefficient is $k = 3.75 \times 10^{21}$.

this case is comparable with the distance from the Sun to the shock and the effects of curvature of the shock considerably reduce the acceleration rate. The nose of the HP, as well as shocks, can be considered as a place where the first-order Fermi acceleration process operates due to the convergence of the plasma flow. However, owing to plasma coupling with interstellar atoms, the intensity of the TS decreases, the additional shock disappears, and the density jump at the HP becomes smaller. As a consequence, the particle acceleration efficiency is not high enough, and diffusion becomes the main process in the region between the TS and HP. The spatial distributions of GCRs (contours of the constant GCRs pressure) for $k = 3.75 \times 10^{21}$ cm^2 s^{-1} and $k = 3.75 \times 10^{22}$ cm^2 s^{-1} are presented in Figure 6. The cosmic ray pressure distributions are strongly asymmetric for small values of the diffusion coefficient. Thus the heliospheric interface has a strong modulation effect on GCRs. It is interesting to note that the downwind part of the TS is not as effective an accelerator of cosmic ray particles for $k \approx 10^{22}$ cm^2 s^{-1} as it is in the case without atoms (paper 1).

4. Discussion

The results presented in the previous section indicate that the heliospheric interface has a strong modulation effect on GCRs. However, GCR influence on the plasma flow pattern is negligible as compared with the influence of H atoms. Is the last conclusion a general feature for the SW/LIC interaction, or is it a consequence of a certain set of model parameters or physical model assumptions?

Before answering these questions, let us note that we adopt here the same parameters of the interstellar plasma component as in paper 1, namely, $V_{p,\mathrm{LIC}} = 25$ km s^{-1} and $T_{p,LIC} = 5680$ K for the unperturbed LIC. These values are close to the most recent measurements of interstellar He parameters by *Witte et al.* [1996] with the Interstellar Neutral-Gas (GAS) instrument on Ulysses. To be more precise, these authors find 24.6 ± 1.1 km s^{-1} for the interstellar helium velocity and 5800 ± 700 K for the helium temperature. However, our numerical experiments (for the two-component LIC model without GCRs) show that an increase of the interstellar temperature up to 6700 K and the interstellar velocity up to 25.6 km s^{-1} does not change shapes and locations of the shocks significantly. We do not expect it otherwise in the three-component model.

We adopted 0.07 cm^{-3} for the interstellar proton number density, as in paper 1. Unfortunately, there are no direct ways to measure the circumsolar interstellar proton (or electron) density. There have been measurements of the average LIC electron density toward nearby stars. However, the resulting densities range from 0.05 (-0,04, +0.14) cm^{-3} up to 0.3 (-0.14,+0.3) cm^{-3} depending on the ion type used for the diagnostics or on which line of sight is probed [e.g., *Lallement and Ferlet*, 1997]. The most precise, temperature-independent value is 0.11 cm^{-3} toward the star Capella [*Wood and Linsky*, 1997]. In addition, what is measured is always averaged over large distances, while the ionization degree in the local interstellar medium is very likely highly variable and out of ionization equilibrium [e.g., *Vallerga*, 1998]. Therefore there is a need for indirect observations which can bring stringent constraints on the plasma density and on the shape and size of the interface. The value 0.07 cm^{-3} used in our calculations is the upper limit given recently by *Izmodenov et al.* [1999a]. These authors have tried to reconcile the SWICS Ulysses pickup ion data, Ly α measurements, and low-frequency radio emissions on the basis of the two-shock, two-component (plasma and H atoms) heliospheric interface model, and have concluded that the most likely value for the interstellar proton density lies in the range 0.04 cm^{-3} $< n_{p,\mathrm{LIC}} <$ 0.07 cm^{-3}. What would happen with the results of the three-component

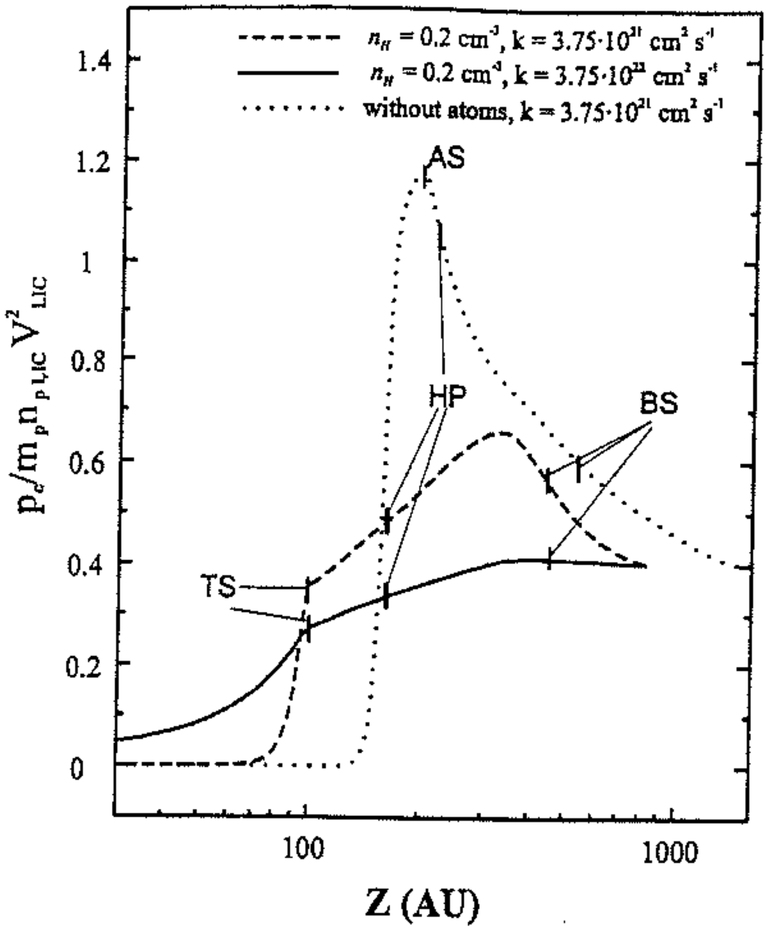

Figure 5. GCR pressure in the upwind direction for two–component (plasma and GCRs) model (dotted lines) and three-component model with two values of diffusion coefficient: $k = 3.75 \times 10^{21}$ cm^2 s^{-1} (dashed line) and $k = 3.75 \times 10^{22}$ cm^2 s^{-1} (solid line). Positions of discontinuties are shown where it is possible.

model if we chose the lower acceptable limit for the proton number density, keeping the other LIC parameters fixed? We can not give a direct answer on this question now and postpone it for the further studies. However, we would like to note here that the influences of both GCRs and interstellar atoms are proportional to $1/n_{p,\mathrm{LIC}}$. Indeed, the GCR influence on the plasma flow is proportional to $p_{c,\mathrm{LIC}}/m_p\ n_{p,\mathrm{LIC}}\ V_{\mathrm{LIC}}^2$ (see paper 1), while the influence of neutrals in the Baranov-Malama model is roughly proportional to $n_{\mathrm{H,LIC}}/n_{p,\mathrm{LIC}}$. Thus it is natural to expect roughly the same relative influence of interstellar neutrals and GCRs on the structure of the plasma flow for other values of $n_{p,\mathrm{LIC}}$.

If, on the contrary, we keep the interstellar proton number density fixed at $n_{p,\mathrm{LIC}} = 0.07$ cm^{-3} as above, but decrease the interstellar atom number density, the influence of GCRs on the flow might increase. To check this, we run the simulations keeping all the parameters as in section 3, but $n_{\mathrm{H,LIC}} = 0.14$ cm^{-3}, as has been chosen by *Baranov and Malama* [1993]. However, even this presently almost unacceptable low value is high enough to make the GCR effects almost unnoticeable. This is true not only for the value $\gamma_c = 5/3$ of the GCR adiabatic index chosen above, but for $\gamma_c = 1.5$ as well. (The latter value of γ_c should be considered as more reliable, since it directly follows from the interstellar spectrum of GCR protons used at present in the modulation theory [e.g., *Webber et al.* 1987; *Reinecke et al.* 1993; also paper 1] with cutoff at 1–2 GeV, while the former value corresponds to pure nonrelativistic particles.) The plasma distribution does not depend on γ_c in the framework of the three–component model (Figure 7a), while the GCR pressure distribution essentially depends on γ_c (Figure 7b). Note, by the way, that in accordance with the results of analytical models of diffusive shock acceleration [*Axford et al.* 1982], the effect of cosmic ray pressure increase at the TS is more pronounced for larger γ_c. The increase of acceleration efficiency when γ_c increases is also the reason that there is a significant influence of the LIC ionization degree on the p_c distribution for $\gamma_c = 5/3$, while we can not see this influence for $\gamma_c = 1.5$ (Figure 7b).

The real value of γ_c depends essentially on the shape of the low–energy portion of the interstellar spectrum of GCRs which is not detected directly. This fact introduces some uncertainty in our model. In addition,

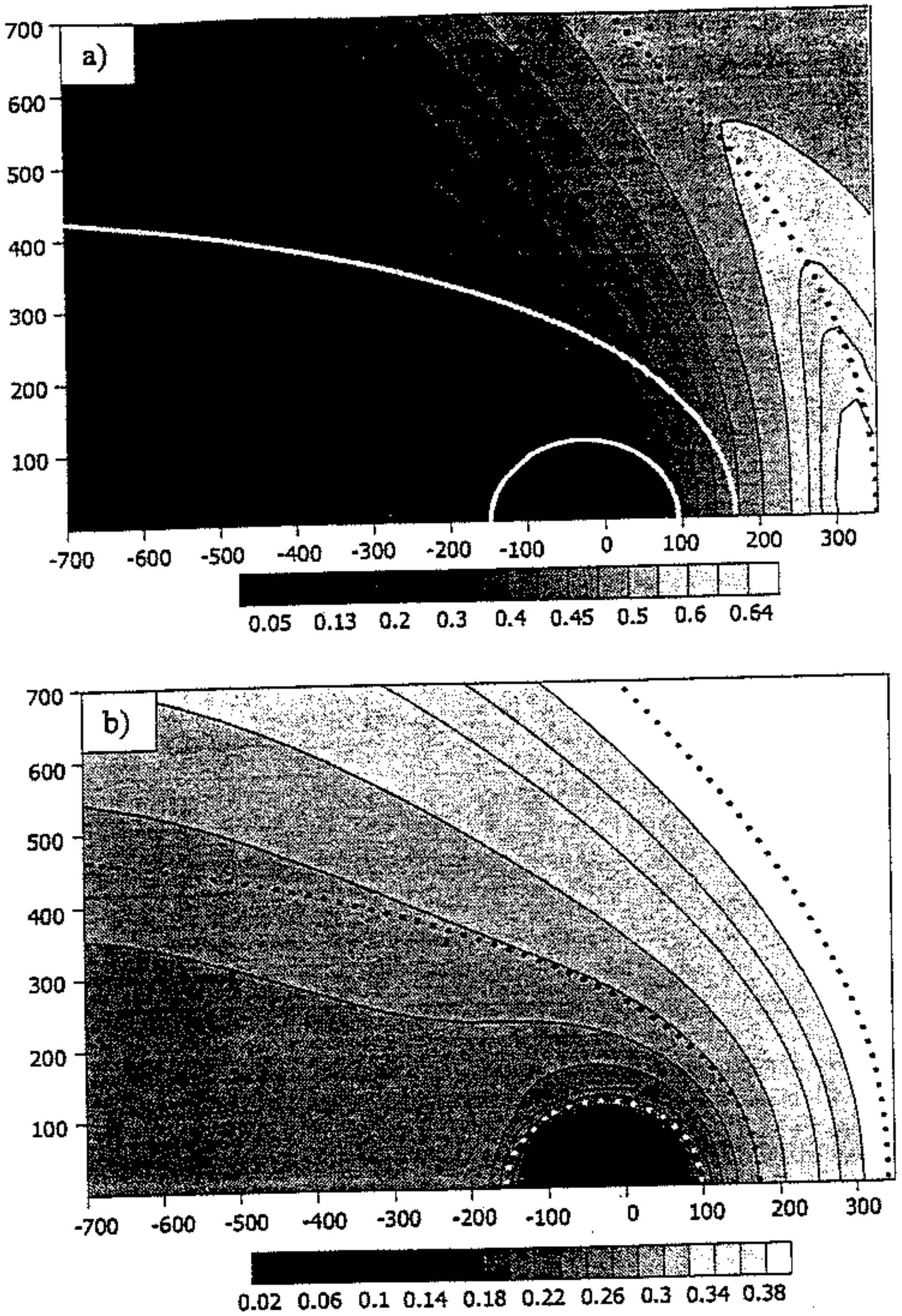

Figure 6. The spatial distributions of the GCRs pressure in the three–component model: (a) $k = 3.75 \times 10^{21}$ cm^2 s^{-1}, (b) $k = 3.75 \times 10^{22}$ cm^2 s^{-1}. Softly fitted discontinuities are also shown by solid or dotted lines.

the value γ_c can have some kind of spatial dependence due to the GCR modulation in the heliosphere. However, this can be taken into account only within the framework of the kinetic description of the cosmic ray transport.

Another point, connected with the uncertainty of the cosmic ray spectra interpretation, is the choice of the diffusion coefficient. The value of the diffusion coefficient is fairly well known only in the inner parts of the heliosphere (inside of the TS), while it is its value in the SW/LIC interaction region that seems to be more important for our model. What happens if the range of the diffusion coefficient is wider than in section 3? In general, the higher the value of the diffusion coefficient, the lower is the influence of cosmic rays (paper 1). On the other hand, for very small values of the diffusion coefficient we also know that the influence of cosmic rays manifests itself manly in the vicinity of the BS if

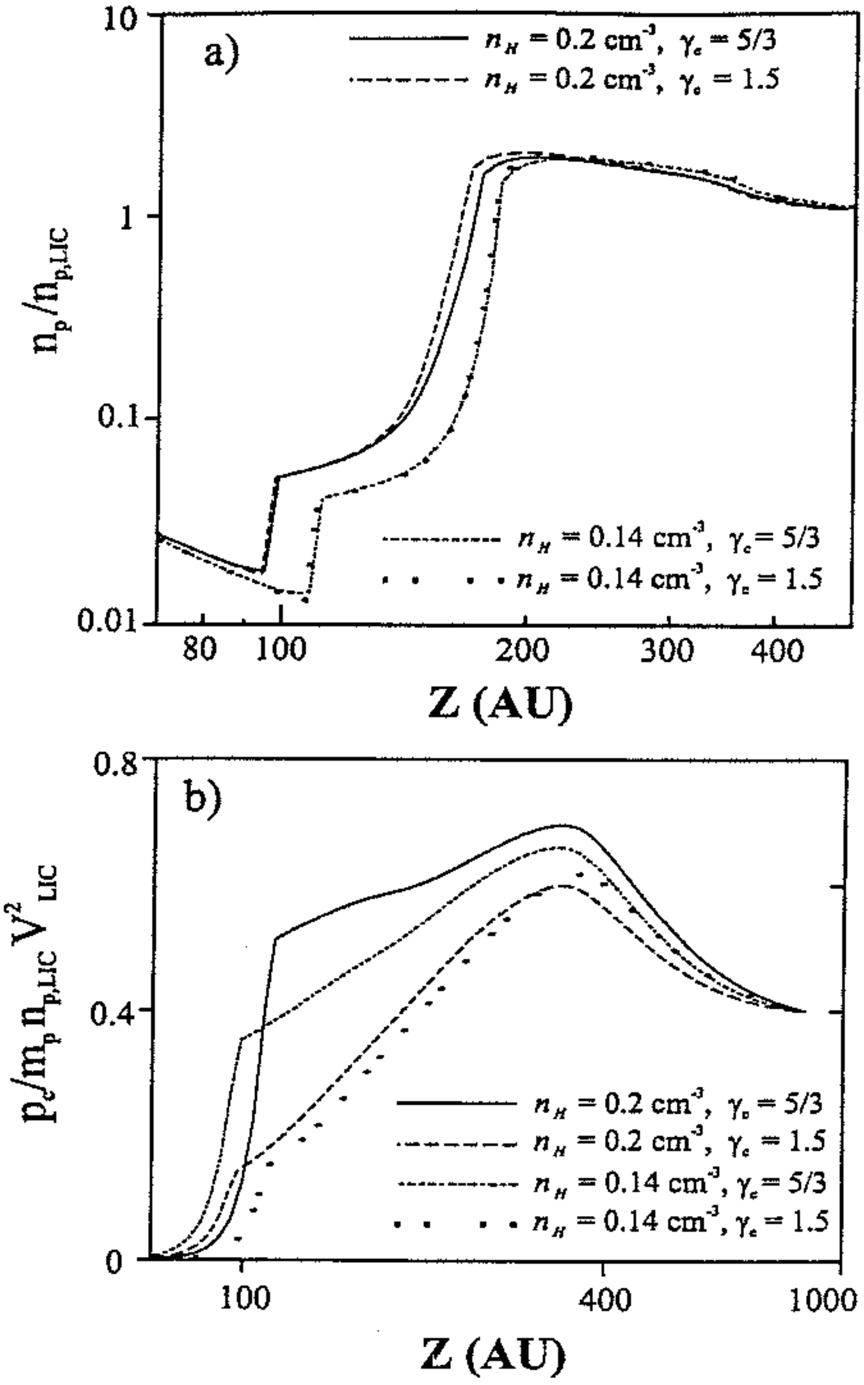

Figure 7. The distributions of (a) the plasma density, and (b) GCRs pressure in the upwind direction for diffusion coefficient $k = 3.75 \times 10^{21}$ cm^2 s^{-1} and several values of n_H and γ_c.

there are no neutrals (paper 1). Thus for small diffusion coefficients we expect that the three-component model results are expected to differ from the two–component model (plasma and atoms) results mainly near the BS.

Finally, to check whether the independence of the flow structure from GCRs is a characteristic feature of the SW/LIC interaction, we doubled the value of $p_{c,LIC}$, keeping other parameters the same as in section 3. The higher value of the cosmic ray pressure is quite realistic due to the possible excess of low–energy particles in the interstellar spectrum of GCRs, the point which remains open at present. For this set, the interstellar plasma flow is subsonic in terms of the effective Mach numbers (paper 1). However the influence of GCRs on the interface plasma is still negligible. This is well understood since the cosmic ray pressure gradients are almost the same as for $\hat{p}_{c,\infty} = 0.4$ (Figure 8).

An important question connected with the results presented above is about the results, applicability to the interpretation of presently existing, or, maybe, forth-

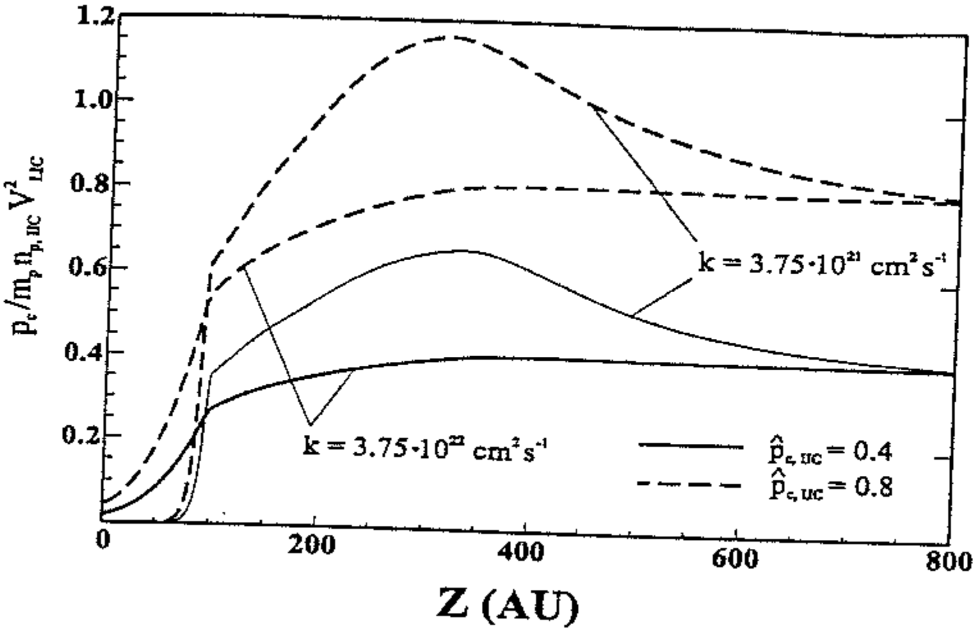

Figure 8. The distributions of the GCR pressure in the upwind direction for several values of diffusion coefficients and interstellar cosmic ray pressure.

coming observational data. In spite of the fact that we used the simplest model of GCR transport in the present study, we believe that the simplest model is good enough to study the GCRs, effect on the plasma flow. Since the influence of GCRs on the plasma and atom distributions (both interstellar and solar) is rather small, we do not need a self-consistent solution for the three-component LIC interaction with the solar wind. The net outcome from this fact is directly related, for instance, to the results of the interpretation of stellar absorption lines toward nearby stars [e.g. *Izmodenov et al.*, 1999b]. Namely, since GCRs do not significantly affect the distribution of both interstellar and "solar" atoms, the interpretations of the Ly α absorption lines based on the two-component SW/LIC interaction model can still be regarded as correct.

The only exception is possible interpretations of the physics related to the BS structure. An example is the source of the quasi-continuous heliospheric 2-kHz emission band registered on Voyager, which, according to *Grzedzielski and Lallement* [1996] can be related to the sharp density distribution at the BS. The results presented above revealed the pure diffusive nature of the BS for diffusion coefficient values less than 3.75×10^{21} cm^{2}s^{-1}. This means that one has to look for another source of the 2-kHz emission, or the diffusive coefficient in our model should be estimated in a more precise way.

The general independence of the flow structure from GCRs does actually open the way to solving the problem of GCR modulation in the heliospheric interface in the frame of a more complex kinetic approximation taking into account the realistic spatial and energy dependences of the diffusion coefficient, since there is no need to use self-consistently the three–component model instead of the two–component one, which is indeed much simpler. We hope that forthcoming synthesis of theoretical cosmic ray spectra with numerous experimental data will provide us with additional knowledge on the heliospheric interface structure and parameters of LIC (D. B. Alexashov and V. V. Izmodenov, manuscript in preparation, 2000).

In the present study we have concentrated only on the effect of GCRs on the interface structure, ignoring a possible effect of anomalous cosmic rays (ACRs) which will be considered in a future paper. This has been mainly done to gain a better insight into the role of each population of energetic particles in the modification of the plasma flow in the interface region. In fact, one can expect a more pronounced influence of ACRs in contrast to GCRs due to smaller values of the energy-averaged diffusion coefficient. ACRs can considerably modify the termination shock structure, and as a result the downstream thermodynamical plasma parameters can differ from those generally accepted.

5. Conclusions

This paper is a continuation of our study of the GCR influence on the structure of the heliospheric interface plasma flow presented in paper 1. However, the model developed here is more realistic and takes into account the mutual influence of plasma, neutral, and cosmic ray components. In the model, GCRs were described hydrodynamically under the assumption that their mass density is negligible, while neutrals were described kinetically. We studied the problem numerically using the global iterations that couple the soft fitting technique for describing plasma and GCR components and Monte Carlo simulations for H atoms. The main conclusions can be summarized as follows.

1. The influence of galactic cosmic rays on the flow pattern is negligible as compared with the influence of H atoms everywhere in the heliospheric interface, except the bow shock, the structure of which can be strongly modified by cosmic rays. The Baranov–Malama model is acceptable therefore for interpretation of the physical processes in the heliosphere if the processes are not related to the bow shock structure.

2. The region of interaction between the solar wind and the interstellar circumsolar cloud has a strong modulation effect on galactic cosmic rays. Although the simplest model of cosmic ray transport is good enough to estimate their influence on the plasma and atom distributions in the heliospheric interface, more advanced models should be used to interpret the observed spectra of cosmic rays.

Acknowledgments. We thank V. B. Baranov for having stimulated this research and for useful discussions and Yu. G. Malama for providing his Monte Carlo code. This work has been done in the frame of the INTAS-CNES cooperative project 97512. "The Heliosphere in the Local Interstellar Cloud." This work has been also supported by the Russian Foundation of Basic Research under grants 98-01-00955 and 98-02-16759. Vlad V. Izmodenov and Artyom V. Myasnikov thank the International Space Science Institute (ISSI) in Bern for partial support. Vlad V. Izmodenov has been also partly supported by a NSF-NATO Fellowship.

Janet G. Luhmann thanks Michael Gedalin and another referee for their assistance in evaluating this paper.

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(Received May 11, 1999; revised October 12, 1999; accepted November 24, 1999.)