MODELING OF THE HELIOSPHERIC INTERFACE: MULTI-COMPONENT NATURE OF THE HELIOSPHERIC PLASMA

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ABSTRACT

In this paper we present a new model of the heliospheric interface - the region of the solar wind interaction with the local interstellar medium. The main advancement of this new model is in multicomponent treatment of charged particles in the heliosphere. All charged particles are divided into several co-moving sorts. The coldest sort with parameters typical for original solar wind protons is considered in the frame of fluid approximation. The hot pickup proton components created from interstellar H atoms and heliospheric ENAs by charge exchange, electron impact ionization and photoionization, are treated kinetically. The charged components are considered in the model self-consistently with interstellar H atoms, which are described kinetically as well. To solve the kinetic equation for H atoms we use Monte Carlo method with splitting of trajectories, which allows 1) to reduce statistical uncertainties for correct interpretation of observational data, 2) to separate all H atoms in the heliosphere into several populations depending on the place of their birth and on the type of parent protons.

1. INTRODUCTION

The heliospheric interface is formed by interaction of the solar wind with the local interstellar medium. During last several years our Moscow group developed models of the heliospheric interface, which follow Baranov & Malama (1993) kinetic-continuum approach and take into account effects of the solar cycle (Izmodenov et al., 2005a), galactic cosmic rays (Myasnikov et al., 2000), interstellar helium ions and solar wind alpha particles (Izmodenov et al., 2003), interstellar magnetic field (Alexashov et al., 2000; Izmodenov et al, 2005b), anomalous cosmic rays (Alexashov et al, 2004; for review, see Izmodenov, 2004). However, all of these models assume immediate assimilation of pickup protons into the solar wind plasma and consider the mixture of solar wind and pickup protons as a single component.

Most of other models also make this assumption (see for review, Zank 1999). However, it is clear from observations (e.g. Gloeckler and Geiss, 2004) that the pickups are thermally decoupled from the solar wind protons and should be considered as a separate population. Moreover, measured spectra of pickup ions show that their velocity distributions are not Maxwellian. Therefore, kinetic approach should be used for this component. Theoretical kinetic models of pickup ion transport, stochastic acceleration and evolution of their velocity distribution function are now developed. However, mostly these models are 1) restricted by the supersonic solar wind region; 2) do not consider back reaction of pickup protons on the solar wind flow pattern, i.e. pickup protons are considered as test particles. Chalov et al. (2003, 2004) have studied properties of pickup proton spectra in the inner heliosheath, but in its upwind part only. Several self-consistent multi-component models (Isenberg, 1986; Fahr et al. 2000; Wang & Richardson, 2001) were considered, however pickup ions in these models were treated in the frame of fluid approximation that does not allow to study kinetic effects.

In this paper we present our new kinetic-continuum model of the heliospheric interface, which treats pickup ions as separate kinetic components. The new model retains the main advantage of our previous models, that is rigorous kinetic description of the interstellar H atom component. Important, that being global (or macro-physical) this model may potentially include all micro-physical phenomena describ-

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ing interaction of solar protons, electrons, pickups, and heliospheric magnetic field fluctuations. Balance of mass, momentum and energy between different components is accounted in the model properly.

2. MODEL

Since the mean free path of H atoms is comparable with the characteristic size of the heliosphere, the kinetic equation for velocity distribution of H atoms $f_{\rm H}(\vec{r}, \vec{v}_{\rm H}, t)$ is solve:

$$\frac{\partial f_{\rm H}}{\partial t} + \vec{v}_{\rm H} \cdot \frac{\partial f_{\rm H}}{\partial \vec{r}} + \frac{\vec{F}}{m_{\rm H}} \cdot \frac{\partial f_{\rm H}}{\partial \vec{v}_{\rm H}} = -(\nu_{ph} + \nu_{\rm impact}) f_{\rm H}(\vec{r}, \vec{v}_{\rm H})$$

$$-f_{\rm H} \cdot \sum_{i=p,pui} \int |\vec{v}_{\rm H} - \vec{v}_i| \sigma_{ex}^{\rm HP} f_i(\vec{r}, \vec{v}_i) d\vec{v}_i \qquad (1)$$

$$+ \sum_{i=p,pui} f_i(\vec{r}, \vec{v}_{\rm H}) \int |\vec{v}^*_{\rm H} - \vec{v}_{\rm H}| \sigma_{ex}^{\rm HP} f_{\rm H}(\vec{r}, \vec{v}^*_{\rm H}) d\vec{v}^*_{\rm H}.$$

were $f_p(\vec{r}, \vec{v}_p)$ and $f_{pui}(\vec{r}, \vec{v}_{pui})$ are the local distribution functions of protons and pickup protons; $\vec{v}_p$, $\vec{v}_{pui}$ and $\vec{v}_{\rm H}$ are the individual proton, pickup proton, and H atom velocities in the heliocentric rest frame, respectively; $\sigma_{ex}^{\rm HP}$ is the charge exchange cross section of an H atom with a proton; ν_{ph} is the photoionization rate; $m_{\rm H}$ is the atomic mass; $\nu_{\rm impact}$ is the electron impact ionization rate; and $\vec{F}$ is the sum of the solar gravitational force and the solar radiation pressure force.

We consider all plasma components (electrons, protons, pickup ions, interstellar helium ions, and solar wind alpha particles) as co-moving media with bulk velocity $\vec{u}$. The plasma is quasineutral, i.e. $n_e = n_p + n_{He^+}$ for the interstellar plasma and $n_e = n_p + n_{pui} + 2n_{He^{++}}$ for the solar wind. For simplicity we ignore the magnetic field. While the interaction of interstellar H atoms with protons by charge exchange is important, this process is negligible for helium due to small cross section. Governing equations for the sum of all ionized components are:

$$\frac{\partial \rho}{\partial t} + div(\rho \vec{u}) = q_1,$$

$$\frac{\partial \rho \vec{u}}{\partial t} + div(\rho \vec{u}\vec{u} + p\hat{I}) = \vec{q}_2 \qquad (2)$$

$$\frac{\partial E}{\partial t} + div([E + p]\vec{u}) = q_3 + q_{3,e}$$

Here $\rho = \rho_p + \rho_e + \rho_{He} + \rho_{pui}$ is the total density of the ionized component, $p = p_p + p_e + p_{pui} + p_{He}$ is the total pressure of the ionized component, $E = \rho(\varepsilon + \vec{u}^2/2)$ is the total energy per unit volume, $\varepsilon = \frac{p}{(\gamma-1)\rho}$ is the specific internal energy.

The expressions for the sources are following:

$$q_1 = n_{\rm H} \cdot (\nu_{\rm ph} + \nu_{\rm impact}), n_{\rm H} = \int f_{\rm H}(\vec{v}_{\rm H}) d\vec{v}_{\rm H},$$

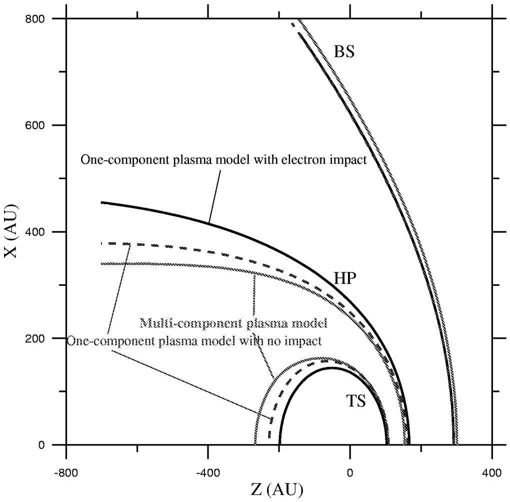

Figure 1. The termination shock, heliopause and bow shock shown for three models of the heliospheric interface: 1) new multi-component model, 2) Baranov & Malama model, 3) Baranov & Malama model with no electron impact.

$$\vec{q}_2 = \int (\nu_{\rm ph} + \nu_{\rm impact}) \vec{v}_{\rm H} f_{\rm H}(\vec{v}_{\rm H}) d\vec{v}_{\rm H} +$$

$$\int\int v_{\rm rel} \sigma_{ex}^{HP}(v_{\rm rel})(\vec{v}_{\rm H} - \vec{v}) f_{\rm H}(\vec{v}_{\rm H}) \sum_{i=p,pui} f_i(\vec{v}) d\vec{v}_{\rm H} d\vec{v},$$

$$q_3 = \int (\nu_{\rm ph} + \nu_{\rm impact}) \frac{\vec{v}_{\rm H}^2}{2} f_{\rm H}(\vec{v}_{\rm H}) d\vec{v}_{\rm H} + \frac{1}{2} \int\int v_{\rm rel} \cdot$$

$$\cdot \sigma_{ex}^{\rm HP}(v_{\rm rel})(\vec{v}_{\rm H}^2 - \vec{v}^2) f_{\rm H}(\vec{v}_{\rm H}) \sum_{i=p,pui} f_i(\vec{v}) d\vec{v}_{\rm H} d\vec{v},$$

$$q_{3,e} = n_{\rm H}(\nu_{\rm ph} E_{\rm ph} - \nu_{\rm impact} E_{\rm ion}),$$

$v_{\rm rel} = |\vec{v}_{\rm H} - \vec{v}|$ is the relative velocity of an atom and a proton, $E_{\rm ph}$ is the mean photoionization energy (4.8 eV), and $E_{\rm ion}$ is the ionization potential of H atoms (13.6 eV).

In addition to the equations of mass, momentum and energy conservation for the total ionized component we solve kinetic equation for the pickup proton component. We assume that the velocity distribution of pickup protons is isotropic (fast pitch-angle scattering), and it is determined in the solar wind rest frame through the velocity distribution function by the expression:

$$f^*_{pui}(\vec{r}, w) = \frac{1}{4\pi} \int\int f_{pui}(\vec{r}\vec{v}) sin\theta d\theta d\phi. \qquad (3)$$

Here $\vec{v} = \vec{u} + \vec{w}$, $\vec{v}$ and $\vec{u}$ are the velocity of a pickup proton and bulk velocity of the plasma component in the heliocentric coordinate system, $\vec{w}$ is the velocity of the pickup proton in the solar wind rest frame, and (w, θ, ϕ) are coordinates of $\vec{w}$ in the spherical coordinate system. The equation for $f^*_{pui}(\vec{r}, w)$ is

$$\frac{\partial f^*_{pui}}{\partial t} + \vec{u} \cdot \frac{\partial f^*_{pui}}{\partial \vec{r}} = \frac{1}{w^2} \frac{\partial}{\partial w} \left(w^2 D \frac{\partial f^*_{pui}}{\partial w} \right) + \quad (4)$$

$$+ \frac{w}{3} \frac{\partial f^*_{pui}}{\partial w} div(\vec{u}) + S(\vec{r}, w),$$

where $D(\vec{r}; w)$ is the velocity diffusion coefficient. The source term $S(\vec{r}; w)$ can be written as

$$S(\vec{r}; w) = \frac{1}{4\pi} \int\int \nu_{ion}(\vec{w}) f_H(\vec{r}, \vec{w} + \vec{u}) sin\theta d\theta d\phi \quad (5)$$

$$- \frac{1}{4\pi} \int\int f^*_{pui}(\vec{r}, w) \nu_H(\vec{w}) sin\theta d\theta d\phi.$$

In equation (5) ν_{ion} and ν_H are ionization rates:

$$\nu_{ion} = \sum_{i=pui,p} \int\int\int f^*_i(\vec{r}, w_i) |\vec{w}_i - \vec{w}| \times$$

$$\sigma^{\mathrm{HP}}_{ex}(|\vec{w}_i - \vec{w}|) w_i^2 dw_i sin\theta_i d\theta_i d\phi_i + \nu_{\mathrm{ph}} + \nu_{\mathrm{impact}},$$

$$\nu_H = \int f_H(\vec{r}, \vec{w}_H) \vec{u} |\vec{w} - \vec{w}_H| \sigma^{\mathrm{HP}}_{ex}(|\vec{w} - \vec{w}_H|) d\vec{w}_H.$$

The effective thermal pressure of the pickup ion component is determined by

$$p_{pui} = \frac{4\pi}{3} \int m_p w^2 f^*_{pui}(\vec{r}, w) w^2 dw. \quad (6)$$

We solve the continuity equations for He$^+$ in the interstellar medium and for alpha particles in the solar wind. Then proton number density can be calculated as $n_p = (\rho - m_{He} n_{He})/m_p - n_{pui}$. Here n_{He} denotes the He$^+$ number density in the interstellar medium, and He^{++} the number density in the solar wind.

In addition to the system of equations (1), (2), (4) we solve the heat transfer equation for the electron component:

$$\frac{\partial \rho_e \varepsilon_e}{\partial t} + div([\rho_e \varepsilon_e] \vec{u}) = \quad (7)$$

$$p_e div \vec{u} + q_{3,e} + Q_{e,p} + Q_{e,pui}.$$

Here $\varepsilon_e = \frac{p_e}{(\gamma-1)\rho_e}$ is the specific internal energy of the electron component, $Q_{e,p}$ and $Q_{e,pui}$ are the energy exchange terms of electrons with protons and pickup ions, respectively.

To complete the formulation of the problem we need to specify: a) diffusion coefficient $D(\vec{r}; w)$, b) exchange terms $Q_{e,p}$, $Q_{e,pui}$, c) behavior of pickup protons and electrons at the termination shock. In principle, our model allows to make any assumptions and verify any hypothesis regarding these parameters. Moreover, the diffusion coefficient $D(\vec{r}; w)$ depends on the level of solar wind turbulence, and equations describing the production (say, by pickups) and evolution of the turbulence need to be added to equations (1)-(7). This work is still in progress and will be described elsewhere.

Table 1. Description of introduced sorts of protons and populations of H atoms.

#	Proton sorts
0	'cold proton sort' consisting of: original solar wind protons + protons originated in region 1 from atoms of population 1.0 + protons originated in region 2 from atoms of populations 2.0, 3, 4
1	protons originated in region 1 from atoms of populations 1.1, 2.0, 3, 4
2	protons originated in region 1 from atoms of populations 1.2, 2.1-2.4
3	protons originated in region 2 from atoms of populations 1.0, 1.1
4	protons originated in region 2 from atoms of populations 1.2, 2.1-2.4

#	H atoms created in:
1.0	region 1 from protons of sort 0
1.1	region 1 from pickup protons of sort 1
1.2	region 1 from pickup protons of sort 2
2.0	region 2 from the solar wind protons
2.1	region 2 from pickup protons of sort 1
2.2	region 2 from pickup protons of sort 2
2.3	region 2 from pickup protons of sort 3
2.4	region 2 from pickup protons of sort 4
3	secondary interstellar atoms (as previously)
4	primary interstellar atoms (as previously)

In this paper we consider as simple model as possible. We adopt $D = 0$. At the termination shock we assume the following condition for the pickup velocity distribution function, which is a consequence of the conservation of magnetic moment of particles:

$$f^*_{2,pui}(\vec{r}, w) = C^{-1/2} f^*_{1,pui}(\vec{r}, w/\sqrt{C})$$

where $C = \rho_2/\rho_1$ is the shock compression. We assume also that $Q_{e,pui} = 0$ and $Q_{e,p}$ is such that

$$T_e = T_p = T_{He^{++}}$$

everywhere in the solar wind. Later, we plan to explore models with more realistic D ,$Q_{e,pui}$ and $Q_{e,p}$ and different microscopic theories can be tested here.

3. RESULTS

Results of new multi-component model calculations with the simplified assumptions mentioned above are shown in Figures 1-5. The termination shock (TS), heliopause (HP) and bow shock (BS) are shown in Figure 1. For the purposes of comparison we present

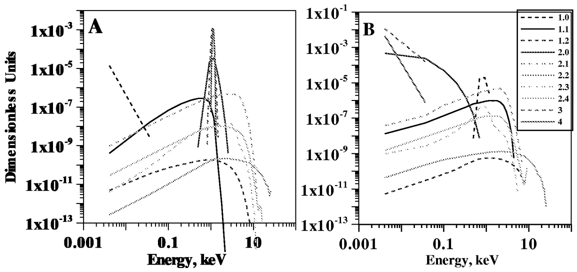

Figure 2. The source function S (eq. (4)) from different populations of H atoms as function of energy shown in the supersonic solar wind at 5 AU (A), and in the inner heliosheath (B).

the location of the TS, HP, and BS for the model, when pickup ions and solar wind protons were considered as a single fluid. Later we refer to this model as Baranov-Malama model (or, shorter, B&M-model). The only (but essential) difference between B&M-model and our new model considered here is that the latter model treats pickups as a separate kinetic component. As is seen from the figure, the differences in locations of the TS, HP, and BS between the new and B&M models are not very large in the upwind direction. The TS is 5 AU further away from the Sun in the new model. In opposite, the HP is 12 AU closer. The effect is much more pronounced in downwind, where the TS moves outward the Sun on ~70 AU. Inner heliosheath region is thinner in the new model as compared with B&M model. The effect of thinner inner heliosheath is partially connected with lower electron temperature and, therefore, smaller electron impact ionization in this region. Indeed, new pickup protons created by electron impact deposit additional energy and, therefore, pressure into the region of their origin, i.e. into the inner heliosheath. The additional pressure pushes the heliopause outward and the TS toward the Sun. To demonstrate this effect, figure 1 shows the results of B&M model but in the case when electron impact is neglected. However, it is seen that the HP is closer and the TS is further from the Sun in the frame of the new multi-component model as compared with B&M model even with no electron impact. This is connected with division of the charged component into several (protons, electrons, pickups) component. Similar effect observed for multi-fluid models of H atoms described in Alexashov & Izmodenov (2005).

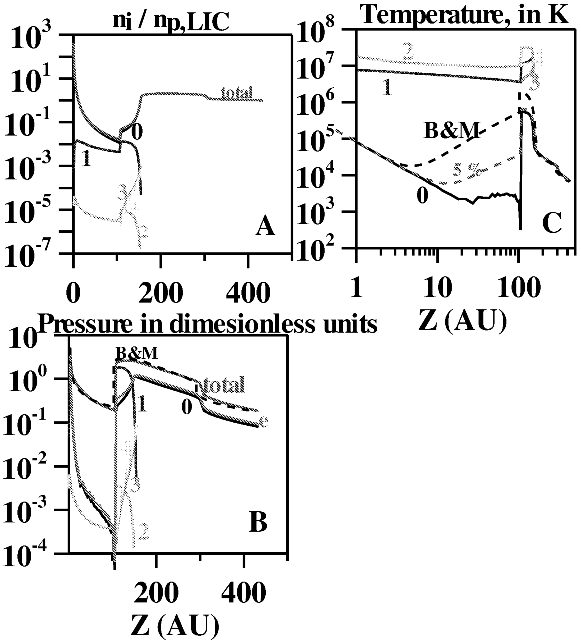

Figure 3. Number densities (A), thermal pressure (B), and temperature (C) of different sorts of protons. Curves are numerated in correspondence with proton sorts.

For better understanding of the results of the new model for the charged and neutral components, we introduce five sorts of charged particles and 10 populations of neutral particles (Table 1). Solar wind protons are noted as sort 0. The pickup protons, which have characteristics close to the solar wind protons, are also added to sort 0. Those are pickup protons created in the supersonic solar wind (region 1, see Figure 1) from H atoms of population 1.0 and pickup protons created in the inner heliosheath (region 2) from H atoms of populations 2.0, 3, 4. The sort 0 is formed in such a way that 1) its thermal pressure is much less than then dynamic pressure everywhere in the heliosphere and, therefore, unimportant; 2) we do not interested in details of the velocity distribution of this population and assume that it is Maxwellian. The rest of pickup protons is divided into four sorts: two sorts are those pickup protons that are originated in region 1, and two other sorts are pickups originated in region 2. In each region we separate pickup protons into two sorts in dependence on their energy. More energetic pickup ions constitute populations 2 and 4. The method of separation of pickup ions into the four populations will be described after introducing H atom populations.

All H atoms in the heliospheric interface we divide into ten populations, which are described in Table 1. First index in the notation of population is the number of region, where the population was originated, i.e. populations 1.0-1.2 are the H atoms created in the supersonic solar wind (region 1), populations 2.0-2.4 are the H atoms created in the inner heliosheath (region 2), populations 3 and 4 are primary and secondary interstellar atoms. Definitions of the two last populations are same as in B&M-model. Second index in notations of H atom population denotes the sort of parent charged particles, i.e. from 0 to 4.

To explain better the reason of separating pickup ions into the four populations we present the source term S (see eq. (4)) of pickup protons in the super-

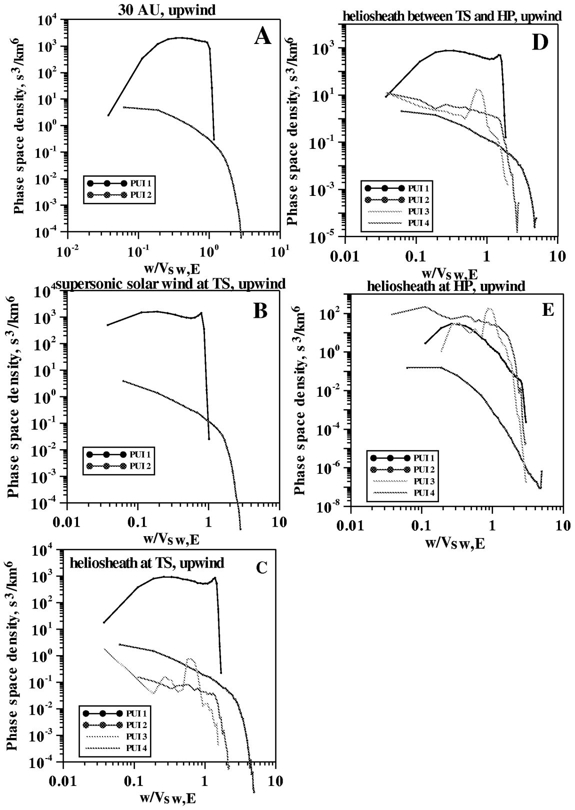

Figure 4. Phase space densities of different sorts of protons in the supersonic solar wind at 30 AU (A), upstream (B) and downstream (C) the termination shock, inside the inner heliosheath (D) and at the heliopause (E). All curves are shown for the upwind direction.

sonic solar wind and in the heliosheath (Figure 2). It is seen that contributions of different H atom populations are very different. In the supersonic solar wind (Fig. 2A) narrow peaks at 1 keV are created by populations 2.0, 3, and 4. These populations are seeds for major population of pickup protons, which we denote as sort 1. Pickup protons created from population 1.1 are also added to sort 1 due to lack of high energy tails (at E¿ 1-2 keV) in their distribution. Pickup protons originated from H atoms of populations 1.2, 2.1-2.4 form sort 2, which is more energetic as compared with sort 1. Similar procedure was done for pickup ions created in the inner heliosheath. It is important to underline here that results of our model do not depend on the way of division of H atoms and pickup ions into populations and sorts. Such division has two goals: 1) to better understand origin of the pickups that are measured by SWICS/Ulysses and ACE (Gloeckler and Geiss, 2004) and ENAs will be measured in the nearest future (McComas et al., this volume), and 2) to obtain better statistics in Monte Carlo method of splitting trajectories.

Number densities, pressures and temperatures for the introduced sorts of charged particles are shown in Figure 3. It is seen (Fig. 3A) that the protons of sort 0 dominate by number density everywhere in the heliosphere, while sort 1 of pickup ions makes up to 20 % of the total number density in the vicinity of the TS. Approaching the HP the number densities of sorts 1 and 2 decrease due to sinks of these populations, and the number densities of sorts 3 and 4 increases. However, since the pickup protons are much more hotter as compared with the solar wind protons of sort 0 (Fig. 3C) the thermal pressure of sort 1 dominates in the inner heliosheath. Downstream of the TS the sort 1 pressure is almost order of magnitude larger than the pressure of sort 0. This is connected with the condition for pickup distribution function, which we adopted at the TS. Expectedly, the temperatures of sorts 2 and 4 are much larger than those of sorts 1 and 3. The temperature of the solar wind protons od sort 0 decreases adiabatically up to 20 AU. Then the temperature becomes so small that energy transferred to the solar wind by photoelectrons becomes non-negligible. Figure 3C presents the temperature of protons calculated in the frame of B&M-model for comparison. Highly unrealistic increase of the temperature is connected with the unrealistic assumption of immediate assimilation of pickup protons into the solar wind. Our new model allows to take into account some energy transfer between solar wind and pickup protons. Curve denoted as "5%" in Figure 3C shows the results of calculations, where we simply assume that 5 % of thermal energy of pickup ions is transferred to protons. This curve qualitatively very similar to Voyager 2 observations. More prominent mechanism of energy transfer between pickup and solar wind protons will be included in the model in future.

Velocity distribution functions of four sorts of pickup protons are shown in Figure 4 for different heliocentric distances in the upwind direction. In the supersonic solar wind sort 1 is dominated at energies below 1 keV, while more energetic sort 2 is dominated for energies above 1 keV. this energetic sort of pickups can form quite-time suprathermal tails that are observed by SWICS/Ulysses and ACE instruments. Downstream of the TS up to the heliopause (Figure 4C-E) the high-energy tails are more pronounced. These high energy pickup ions form energetic population of H atoms, which are known as ENAs (e.g. Gruntman et al., 2001).

Figure 5 presents differential fluxes of different populations of H atoms at 1 AU. It is seen that different populations of H atoms are dominating at different energies. At the highest energies of above 10 keV population 2.2 dominates. This population consists of atoms created in the inner heliosheath from hot pickups of sort 2. In the energy range of 0.2-6 keV population 2.1 dominates. This population consists of atoms created in the inner heliosheath from hot pickups of sort 1. Since the both populations are

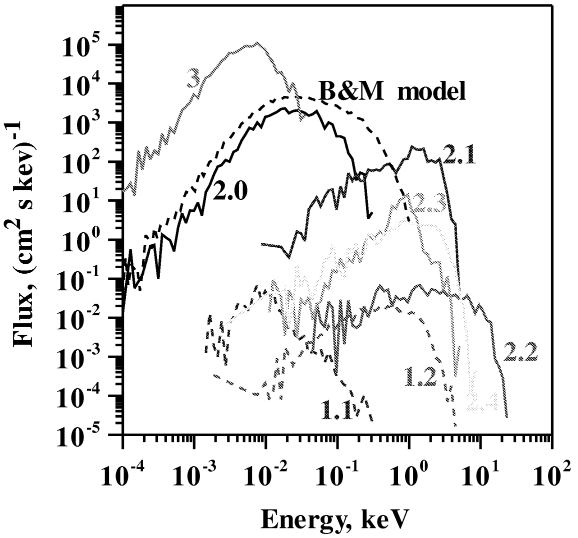

Figure 5. Fluxes of H atoms of populations 1.1,1.2, 2.0-2.4 and 3 at 1 AU in the upwind direction as functions of energy.

originated in the inner heliosheath the measurements of these energetic particles as planned by IBEX will provide us robust information on the properties of the inner heliosheath and, particulary, on the behavior of pickup ions in this region. Note, also, that there is significant difference in the ENA fluxes predicted in the frame of one- and multi- component models.

4. CONCLUSIONS

We have developed new self-consistent kinetic-continuum model, which absorbs the main advantage of our previous models, i.e. rigorous kinetic description of the interstellar H atom flow, and makes significant step forward by taking into account pickup protons as a separate kinetic component. New model is very flexible and allows to test different scenarios for the pickup component inside, outside and at the termination shock. The model allows to treat electrons as a separate component and to consider different scenarios for this component. We have created a new tool which could serve for interpretation of pickups and ENAs as well as all diagnostics, which are connected with the interstellar H atom component. New model requires more exact description of physical process involved as compared with previous non self-consistent models. It is shown that the heliosheath becomes thinner and termination shock is further from the Sun in the new model as compared with B&M model. Heliopause, in opposite, is closer.

The main methodological advancements made in the reported model, which was not discussed in this paper, is that we successfully applied Monte Carlo method of splitting trajectories to non-Maxwellian velocity distribution function of pickup protons. The splitting of trajectories allows us to essentially improve the statistics of our method and to calculate differential fluxes of ENAs at 1 AU with high level of accuracy. It was demonstrated in the paper that ENAs originated from different sorts of pickup protons dominate in different energy ranges that allows to determine nature of the heliosheath plasma flow.

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