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KINETIC VS MULTI-FLUID MODELS OF H ATOMS IN THE HELIOSPHERIC INTERFACE

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ABSTRACT

The goal of presented study is to illuminate similarities and differences in the kinetic and multi-fluid models of the heliospheric interface, the region of solar wind interaction with the Local Interstellar Cloud (LIC), and then to explore physical reasons for these differences. We outline differences of two types of models. The first type is based on a kinetic description of the interstellar H atom flow, which is required for this problem due to the fact that the mean free path of H atoms is comparable to the characteristic size of the heliospheric interface. The second type of model is based on a voluntary assumption that the flow of H atoms can be described hydrodynamically by a set of Euler equations (one-fluid approach) or by 2, 3, and 4 sets of Euler equations for different populations of H atoms (thus 2-, 3-, or 4- fluid models). It is shown that differences are significant between kinetic and multi-fluid models in observationally meaningful measurements such as the location of the termination shock and heliopause, the filtration of H atoms through the heliospheric interface, and the velocities and temperatures of H atoms. Therefore, the multi-fluid models may lead to incorrect interpretation of observational data.

Key words: Sun: solar wind — interplanetary medium — ISM : atoms.

1. INTRODUCTION

In contrast to the plasma component, which deviates at the heliopause, interstellar hydrogen atoms (H atoms) penetrate deep into the heliosphere. Inside the heliosphere at one or several AU the H atoms and their derivatives, such as pickup ions and anomalous cosmic rays (ACRs), can be measured. The momentum transfer cross sections of elastic H-H, H-p collisions are negligible as compared with the charge exchange cross section (Izmodenov et al. 2000). The charge exchange process strongly influences the properties of the H atom gas in the interface. Hydrogen atoms newly created by charge exchange have the velocities of their ion partners in the charge exchange collisions. Therefore, the parameters of these new atoms depend on local plasma properties. It is convenient to distinguish four different populations of H atoms: 1) atoms created in the supersonic solar wind (so-called neutral solar wind), 2) atoms originating in the inner heliosheath and known as heliospheric ENAs , 3) atoms created in the disturbed interstellar wind, 4) original (or primary) interstellar atoms. The strength of H atom-proton coupling can be estimated by calculating mean free path of H atoms in plasma. It could be shown (e.g., Izmodenov, 2000) that the mean free paths of the H atom populations with respect to charge exchange with protons are comparable to or larger than the size of the heliospheric interface. Therefore, the kinetic Boltzmann approach must be used to describe interstellar atoms in the heliospheric interface correctly.

The first self-consistent model of the heliospheric interface has been suggested by Baranov et al. (1991) and developed by Baranov and Malama (1993). Further development of kinetic models by Moscow group are summarized in Izmodenov (2004).

Even through the interstellar H-atoms were described kinetically in the first self-consistent Baranov-Malama model, one-fluid and multi-fluid descriptions of the interstellar H atom component in the heliospheric interface were extensively employed in quite large number of publications. The one-fluid approach assumes that the velocity distribution function of H atoms is Maxwellian. This assumption is actually equivalent to the assumption of effective elastic H-H collisions, of weak H-p elastic collisions and a weak charge exchange. In other words, it is assumed in the one-fluid model that the mean free

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Table 1. Distances to the termination shock, heliopause, and bow shock in the upwind direction in AU (%)

Set	Termination Shock	Heliopause	Bow Shock
K	87 (100%)	130 (100%)	245 (100%)
$F1$	101 (+16%)	139 (+6.8%)	207 (-15%)
$F2$	93 (+7.9%)	139 (+6.9%)	228 (-7%)
$F3$	94 (+8%)	144 (+10.8%)	234 (-4.5%)
$F4$	91 (+4.6%)	141 (+8.5%)	254 (+3.7%)

path of H atoms, calculated with respect to H-H collisions, is much smaller than both the characteristic size of the problem and the mean free path, calculated with respect to charge exchange. In the multi-fluid approaches all H-atoms are divided into several populations depending on the model, then it is assumed that each population can be described by Euler's equations for ideal fluids. The total velocity distribution function of H atoms is assumed to be the sum of the Maxwellian velocity distributions of different populations.

In this paper we come back to comparison of the kinetic and multi-fluid models of the heliospheric interface (see, also, Baranov et al., 1998; and Alexashov and Izmodenov, 2005, for details). We want to explore differences in the models for values that can be determined from available spacecraft data: 1) distances to the termination shock and the heliopause, 2) the number density, velocity, and temperature of the interstellar H atoms at the heliospheric termination shock.

The second goal of this paper is to clarify the physics of the difference between kinetic and multi-fluid models. This might possibly lead to future improvements in the simplified multi-fluid models to make them more appropriate for dealing with some aspects of heliospheric interface modelling.

2. MODELS

For the purposes of comparison in this work we restrict ourselves to as simple an two-component (palsma and H atoms) axisymmetric model of the heliospheric interface as possible. Detail description of the models and used boundary conditions could be found in Alexashov and Izmodenov (2005).

In the continuum-kinetic model (Baranov-Malama or B&M model), hydrodynamic equations for the charged component are solved self-consistently with the kinetic equation for the velocity distribution function of H atom component.

It is supposed in multi-fluid models that H-atoms in the heliospheric interface can be divided into N populations, and the velocity distribution functions of these populations are locally Maxwellian with parameters ρ_i, $\vec{V}_i$ and T_i, where $i = \overline{1, N}$. Since H atoms newly created by charge exchange have properties of the local protons, it is very convenient to divide H atoms into several populations depending on the place of their origin. Therefore, atoms of population i originate in region i of the heliospheric interface. Note, that for a one-fluid model of H atoms $N = 1$, and all H atoms in the heliospheric interface are considered as one fluid. Different populations of H atoms do not interact each with other, but they interact with the plasma component by charge exchange. Governing equations for i-component of H atoms are given in Alexashov & Izmodenov (2005). For the purpose of comparison with our kinetic model we developed four different multi-fluid models (models $F1$, $F2$, $F3$, and $F4$). In **model F1** we do not divide H-atoms into sub-populations and consider all H-atoms as a single fluid. This model corresponds to the description of H-atoms by Fahr et al. (2000). It is important to note here that to get a steady solution in the one-fluid model we neglected the H atoms originating in the supersonic solar wind, although massloading of the solar wind plasma was taken into account properly, a similar procedure was followed by Fahr et al. (2000). Note that here, unlike in other papers, N-fluid model means N-fluid approach used for H atoms flow. In the **model F2** H-atoms are separated into two populations: 1) atoms originated (by charge exchange) in the heliosphere inside the heliopause; 2) atoms originating in the interstellar medium outside the heliopause including primary interstellar H atoms. As described in the previous section, each of the two populations is assumed to

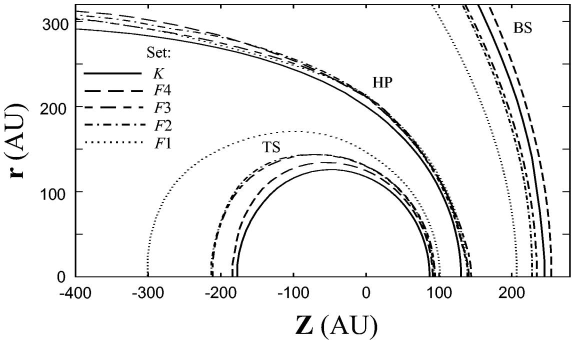

Figure 1. The termination shock, heliopause and bow shock for the self-consistent models K and F1-F4. The models details are given in Section 2. TS, HP and BS are designations of termination shock, heliopause and bow shock, respectively. The solid (K), dashed (F4), long-short dashed (F3), dashed-dotted (F2) and dotted (F1) curves correspond to kinetic, four-fluid, three-fluid, two-fluid and one-fluid H-atom models, respectively. Z is the heliocentric distance (in AU). Axis OZ is directed towards the interstellar gas flow.

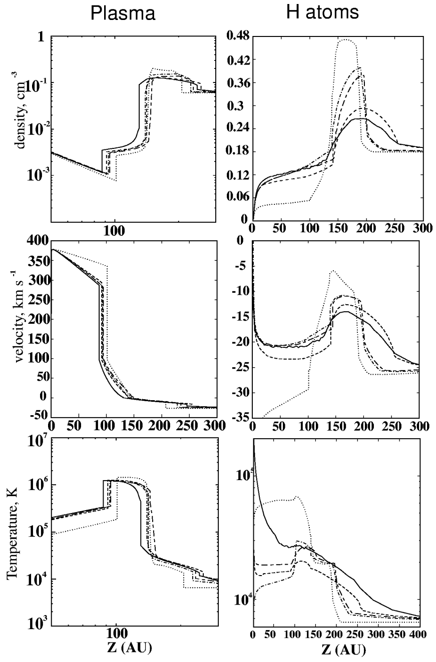

Figure 2. The number densities, bulk velocities, and temperatures of plasma (left) and H atom(right) components in the upwind direction for the self-consistent kinetic (K) and multi-fluid models, F1-F4. The total number density of H atoms represents the sum of number densities of all populations. In the case of multi-fluid models, the bulk velocity and temperature were calculated as weighted averages of the bulk velocities and temperatures of all components. The solid (set K), dashed (set F4), long-short dashed (set F3), dashed-dotted (set F2), and dotted (set F1) curves correspond to kinetic, 4-fluid, 3-fluid, 2-fluid and 1-fluid models, respectively.

have a Maxwellian distribution function. In **model F3** we divide atoms created inside the heliopause into two populations: 1) atoms created in the supersonic solar wind region inside the TS; 2) atoms created in the inner heliosheath, the region between the TS and HP. Therefore, it is assumed in this model that the velocity distribution of H atoms in the heliospheric interface is a sum of three Maxwellian. This model corresponds to the description of H atoms chosen in Zank et al. (1996), etc. Finally, in **F4 model** H atoms in the heliospheric interface are divided into four populations: 1) atoms created in the supersonic solar wind region inside the TS; 2) atoms created in the inner heliosheath, the region between the TS and HP; 3) atoms created in the outer heliosheath between the HP and BS; and 4) primary interstellar H atoms entering the interface from pristine interstellar medium.

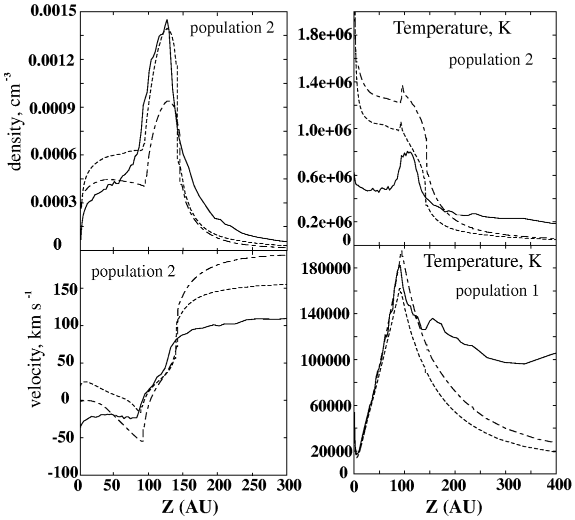

Figure 3. The density, bulk velocity, and temperature of populations 2 and temperature of population 1 atoms in the upwind direction. The solid (set K), dashed (set F4), and long-short dashed (set F3) curves correspond to kinetic, 4-fluid, and 3-fluid self-consistent models respectively.

3. RESULTS AND CONCLUSIONS

We compare the self-consistent kinetic (Baranov-Malama) model of the heliospheric interface (set "K") to four self-consistent multi-fluids models $F1-F4$, which were described in Sect. 2. The results of comparisons are presented in Tables 1 and 2 and Figures 1-3. Detailed discussions of the comparison are given in Alexashov and Izmodenov (2005) and can be summarized as following:

1. It was shown that the differences in number density, velocity, and temperature of the interstellar H atoms inside the heliosphere and at the termination shock obtained in the kinetic and multi-fluid models are significant. Therefore, using the multi-fluid models will affect how observational data are interpreted, including pickup ion spectra measured onboard Ulysses and ACE and backscattered solar Lyman-alpha radiation measured by SOHO/SWAN, HST, Voyager 1 and 2, Pioneer 10, etc. The same conclusion can be made for the fluxes of the atoms originating in the inner heliosheath, which are known as the heliospheric ENAs and will be measured by Interstellar Boundary Explorer (http://www.ibex.swri.edu) in the very near future.

2. The fundamental difference between the kinetic and multi-fluid approaches for the H atom component in the heliospheric interface is that the multi-fluid models are based on voluntary assumption that the flow of H atoms can be described hydrodynamically by a set of Euler equations (one-fluid approach)

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Table 2. Density, bulk velocity, and temperature of different populations of H atom in the outer heliosphere at 80 AU in upwind

		Number density,	cm^{-3}	
	1	2	3	4
K	$0.26 \cdot 10^{-3}$	$0.91 \cdot 10^{-3}$	0.058	0.076
$F4$	$0.27 \cdot 10^{-3}$	$0.62 \cdot 10^{-3}$	0.054	0.059
$F3$	$0.30 \cdot 10^{-3}$	$0.41 \cdot 10^{-3}$	0.14	—
$F2$	$0.29 \cdot 10^{-3}$	0.14	—	—
$F1$	0.053	—	—	—
		Velocity,	km/s	
	1	2	3	4
K	+328.	-5.8	-15.0	-26.9
$F4$	+335.	-16.2	-20.0	-28.0
$F3$	+328.	-54.	-20.5	—
$F2$	+330.	-20.4	—	—
$F1$	-29.	—-	— 8	—
		Temperature,	K	
	1	2	3	4
K	182500	67335	15490	7100
$F4$	162200	978590	16000	6760
$F3$	195100	1218440	15630	–
$F2$	194100	14870	—	–
$F1$	64198	—	—	–

or by 2, 3, and 4 sets of Euler equations for different populations of the H atoms (2-, 3-, or 4- fluid models, respectively). Physically, this assumption means that the mean free path of H-H collisions between the H atoms of one population is effectively smaller than both the characteristic size of the problem and the mean free path with respect of charge exchange. At the same time, H-H collisions between H atoms of different populations are ignored in the multi-fluid approaches.

3. By a number of numerical tests for different cross-sections, different temperatures of the background plasma, and different outer sources of the interstellar particles, we established that the fundamental reason for the difference in the results of the kinetic and four-fluid models for the primary interstellar H atom component lies in different 'zone of influences' of the solution in the kinetic and fluid approximations. In other words, the reason for the difference is in the amount of particles that come from the side of the streamlines of the H atom flow and contribute to the velocity distribution of H atoms. In the kinetic model particles from the sides are contribute easily to the H-atom population at a certain point due to their large mean free paths. In the fluid approaches, the flow outside of a flux-tube could indirectly contribute through the change in the streamlines and, therefore, in the tube size. The behavior of flow in the fluid-models is determined by artificially introduced H-H collisions among the atoms inside of one-population.

4. The results obtained with the four-fluid model, which describes interstellar H-atoms as a sum of four Maxwellian populations, are the closest to results of kinetic description compared to other multi-fluid models. By comparing the kinetic and four-fluid models we established that approximation of the source terms in the plasma Euler's equations by McNutt et al. (1998), which assumes that the velocity distribution function of H atoms is the sum of four shifted Maxwellians, is not the main source of discrepancies between kinetic and multi-fluid models. At the same time the use of this approximation for the source terms in one-,two-,three- fluid models results in large differences with the kinetic model.

5. Finally, from the consideration above and fundamental differences between kinetic and fluid approximations, we conclude that we cannot find any way to improve the multi-fluid models of H atoms in order for their results to approach those of the kinetic model. Instead, the kinetic approach should be used for future 3D modelling of H atoms in the heliospheric interface.

Significant new constraints on the heliospheric interface models will be obtained in the nearest future. Comparison of model predictions with data will determine whether the models described above and their future progress will be able to explain the observational data adequately. However, it is important that the models used for the interpretation should have a solid theoretical background.

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