Kinetic-gasdynamic modeling of the solar wind interaction with the partly-ionized local interstellar medium

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The heliospheric interface is the region of the solar wind interaction with the local interstellar medium (LISM)

Early theoretical models of the heliospheric interface

These models assume that LISM is fully ionized!

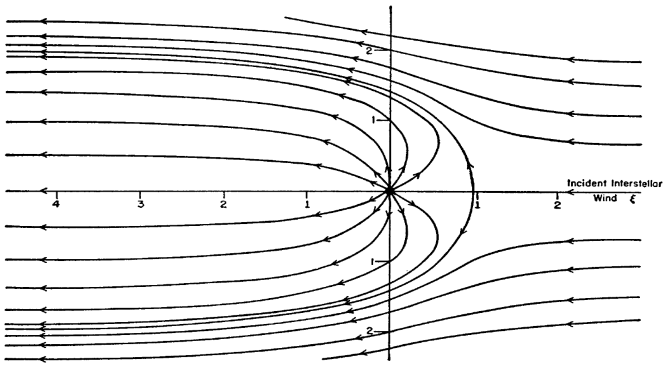
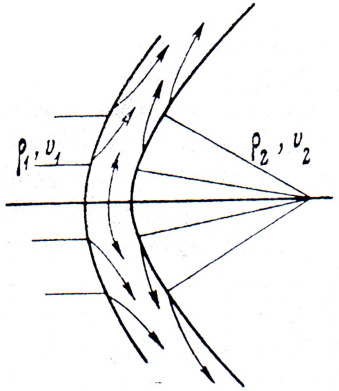


FIG. 1.—The streamlines of the subsonic, nearly incompressible, hydrodynamic flow of a stellar wind beyond the shock transition ($r = R$) in the presence of a subsonic interstellar wind carrying no significant magnetic field.

Parker (ApJ 1961);



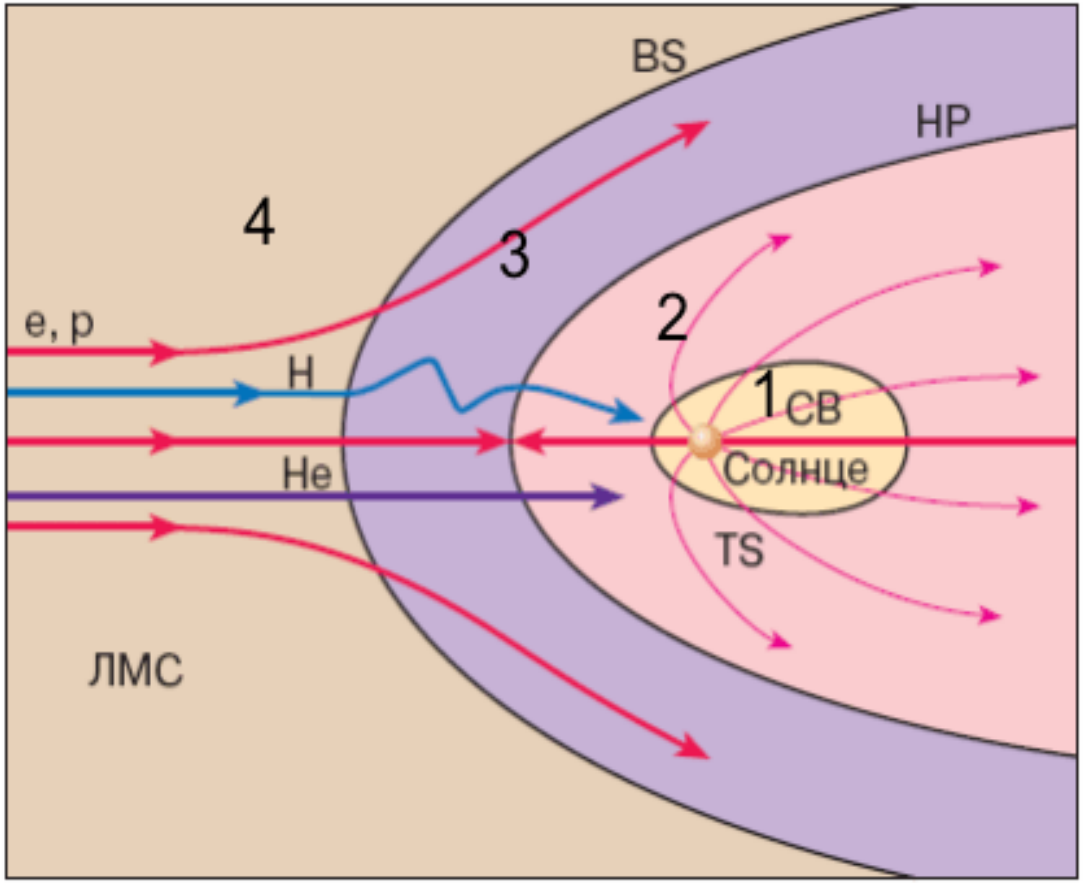
Baranov, Krasnobaev, Kulikovskii (1970, Soviet Acad. Science Reports)

Penetration of interstellar neutrals: Patterson et al. (1963), Dessler (1967), Blum and Fahr (1970)

First (indirect) determination of interstellar H atoms: OGO5 (Bertaux and Blamont, 1971; Thomas and Krassa, 1971);

IN 70-80x IT WAS REALIZED THAT ROLE OF INTERSTELLAR NEUTRAL COMPONENT IS IMPORTANT;

INTERSTELLAR H ATOMS INTERACT WITH PLASMA COMPONENT BY CHARGE EXCHANGE



Interstellar neutrals determine or influence all physics of the heliospheric interface

The mean free path of the interstellar atoms is comparable to the distance to the heliopause (~ 150 AU) => kinetic approach is required

Baranov, Malama (1993, J. Geophys. Res.)

Euler equations for the plasma component

$$\nabla \cdot \rho \vec{V} = 0,$$
$$(\vec{V} \cdot \nabla \vec{V}) + (1/\rho)\nabla p = \vec{F}_1[f_H(\vec{r}, \vec{w}_H), \rho, \vec{V}, p],$$
$$\nabla \cdot [\rho \vec{V}(\varepsilon + p/\rho + V^2/2)] = F_2[f_H(\vec{r}, \vec{w}_H), \rho, \vec{V}, p],$$
$$p = (\gamma - 1)\rho\varepsilon,$$

Kinetic equation for H atom component

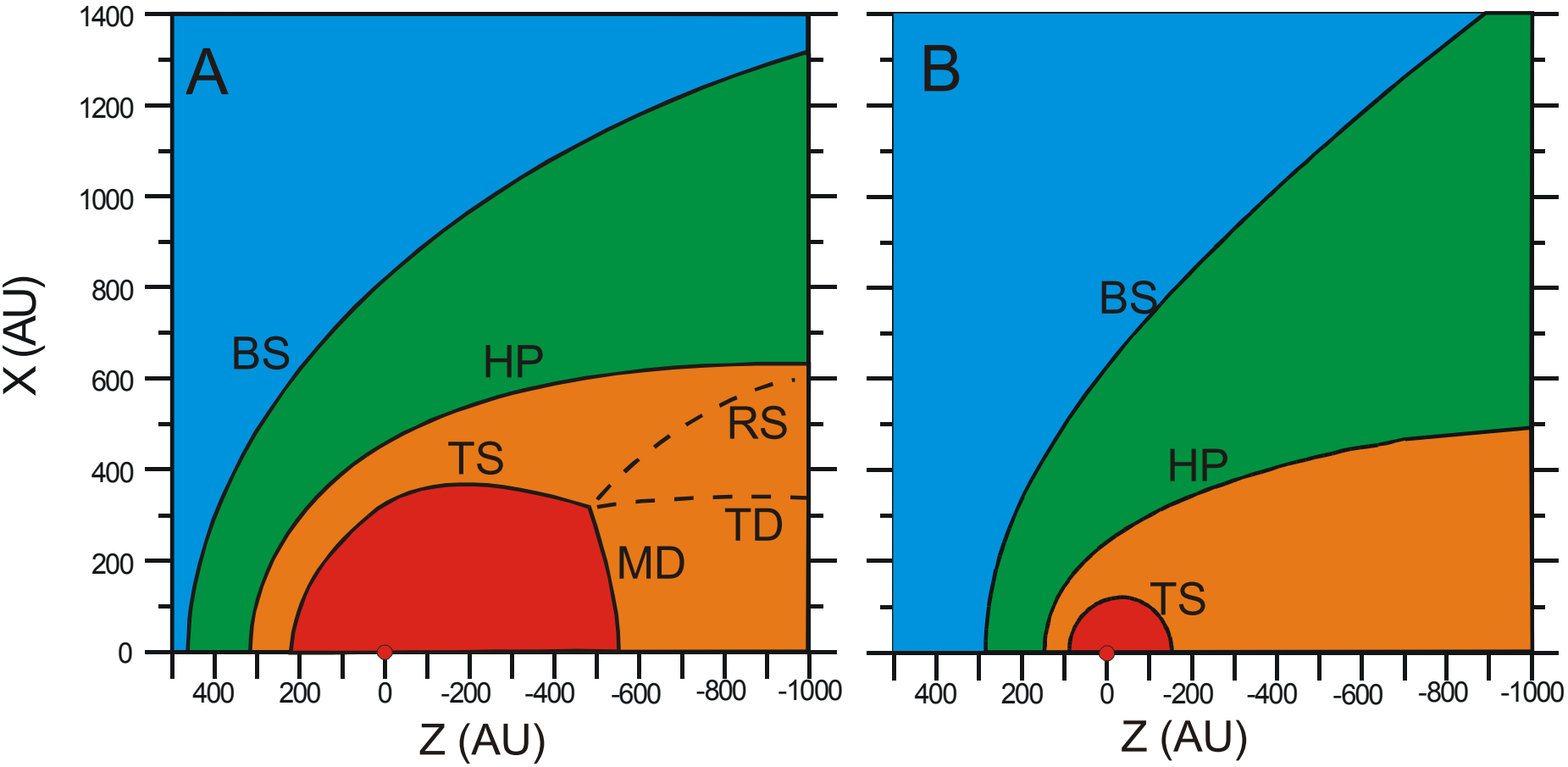
$$\vec{w}_H \cdot \frac{\partial f_H(\vec{r}, \vec{w})}{\partial \vec{r}} + [(\vec{F}_r + \vec{F}_g)/m_H] \cdot \frac{\partial f_H(\vec{r}, \vec{w}_H)}{\partial \vec{w}_H} =$$
$$f_p(\vec{r}, \vec{w}_H) \int \mid \vec{w}'_H - \vec{w}_H \mid \sigma f_H(\vec{r}, \vec{w}'_H) d\vec{w}'_H -$$
$$f_H(\vec{r}, \vec{w}_H) \int \mid \vec{w}_H - \vec{w}_p \mid \sigma f_p(\vec{r}, \vec{w}_p) d\vec{w}_p$$

Modern multi-component kinetic-gasdyn. models of the heliospheric interface take into account:

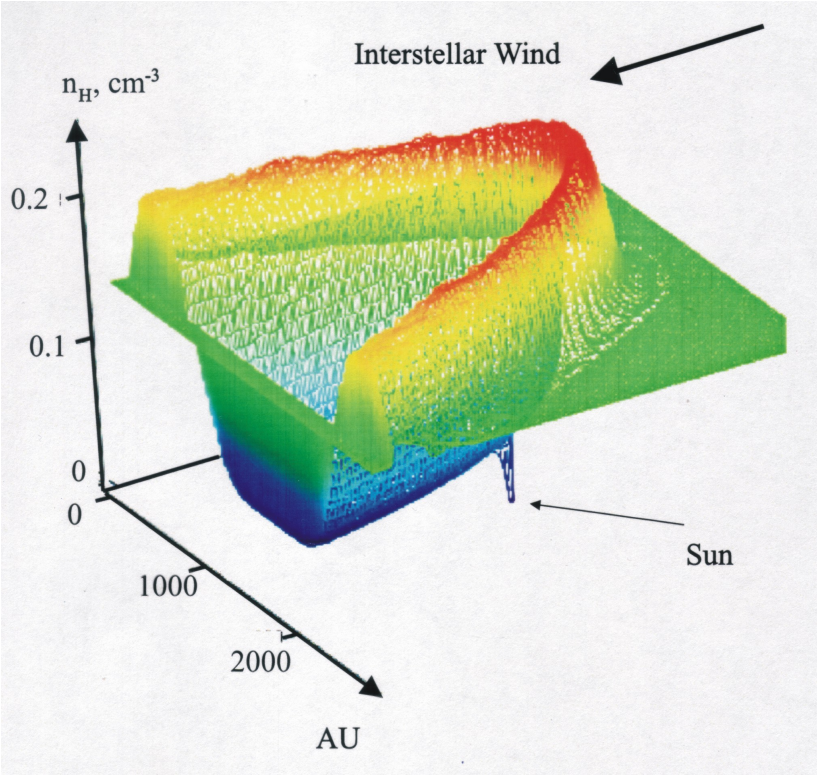
Component or Effect	Reference *
Interstellar H atoms (kinetic description)	Baranov & Malama JGR1993; Izmodenov et al. JGR 2001
Interstellar plasma (protons, electrons helium ions);	Baranov & Malama JGR1993; Izmodenov et al. ApJ 2003
Interstellar magnetic field	Izmodenov, Alexashov & Myasnikov, A&A 2005
Galactic and Anomalous Cosmic Rays	Myasnikov et al. 2000 Alexashov et al. 2004
solar wind (protons, electrons, alpha-particles);	Baranov & Malama JGR1993; Izmodenov et al. ApJ 2003
Pickup ions (kinetic description);	Malama et al. A&A 2005
Solar Cycle Variations of the solar wind	Izmodenov et al. 2005, 2008
Latitudinal variations of the solar wind	Alexashov,

* Only works of Russian group; Other groups contribute significantly (e.g. Zank, Opher, Gombosi, Fahr, etc.)

How does charge exchange modify the plasma flow?



Hydrogen wall is an increase of the number density of interstellar H atoms around the heliopause of the Sun. The hydrogen wall is created due to charge exchange of primary H atoms with decelerated in the vicinity of the heliopause interstellar protons.



Predicted: Baranov, Lebedev, Malama (ApJ 1991)

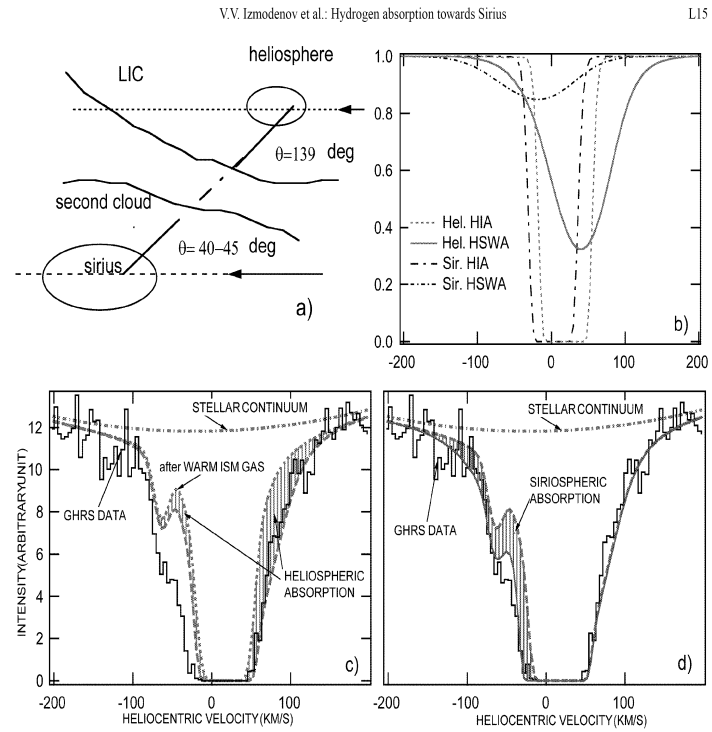
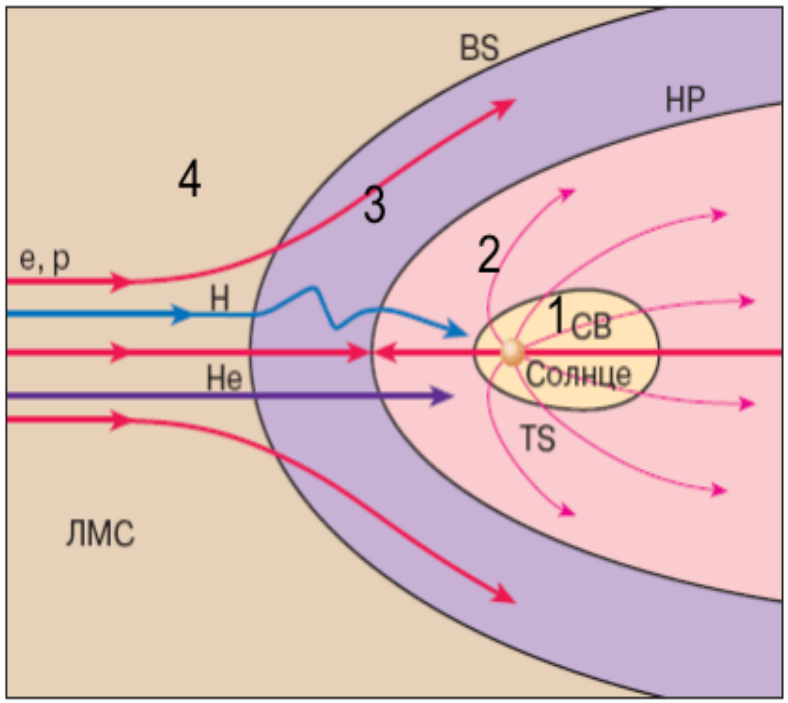


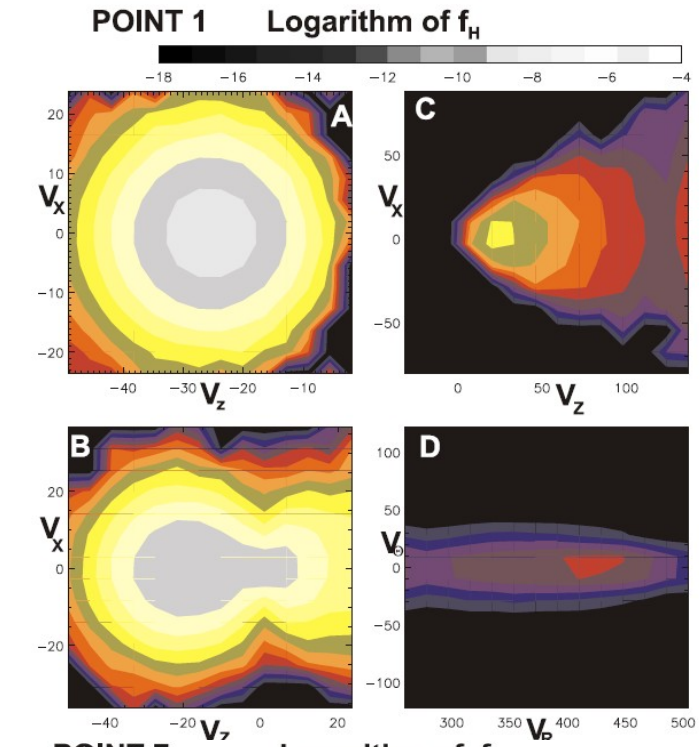
Fig. 1. a Schematic view of the Sun-Sirius line-of-sight. **b** Transmission as a function of Doppler shift in the solar rest frame through heliospheric HIA's and HSWA's in the direction of Sirius, and through the siriospheric H atoms in conditions described in the text. **c** The GHRS spectrum, the simulated profile after ISM absorption, and the profile after ISM + heliospheric absorption. **d** Simulated profile after ISM + Heliospheric + Siriospheric absorption, where a good fit to the data is obtained for a column density of HIA and HSWA atoms two times the heliospheric column for the same orientation.

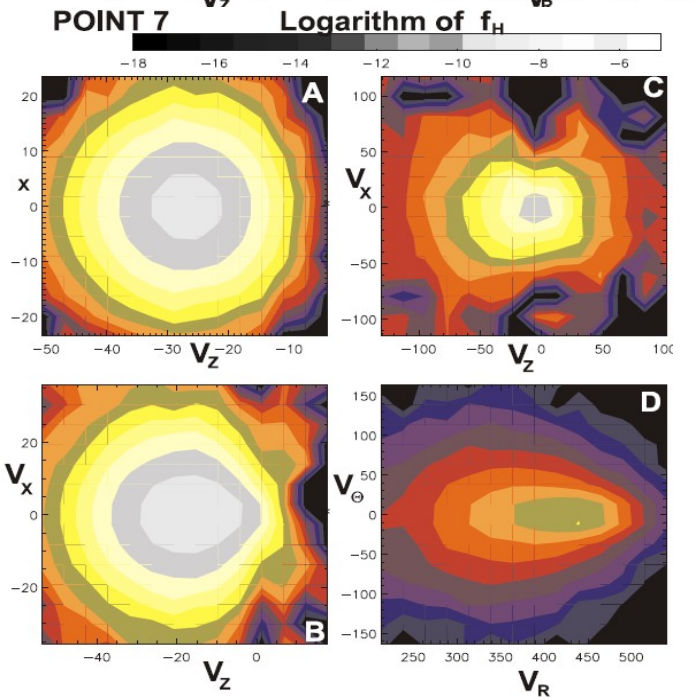
Discovered by Linsky and Wood (ApJ 1996) in Lyman-alpha absorption spectra toward Alpha-Cen.

Later the heliospheric absorption was discovered toward other stars (e.g.Wood et al. 2000; Izmodenov et al. 1999; review: Wood 2005).
This discovery open new way to diagnose stellar winds by studying the stellar absorption and has some implication on the history of the solar system

Velocity distribution function of the 4 populations of H atoms in the outer and inner heliosheathes







Izmodenov, Space Sci. Rev, 2001

Difficulty in the Monte-Carlo modeling: geometry of the problem

- Probability for a particle from ~1000 AU to reach 1 AU (where the most of observations appear) is 10^{-6}
- Splitting of trajectories is required
- Malama (1991) proposed geometrical and physical splitting; that includes geometrical

  splitting of the secondary H atoms; All calculations performed on PC (no real need in supercomputers exept new model with non-maxwellian pickup proton population)
- New (simplified) splitting procedure (Malama 2009) improves time of calculations (for the same statistics) in 4-5 times (applied for new new model with non-maxwellian pickup proton population)

Non-Maxwellian behaviour at TS is essential: two-step procedure would not work properly

(Katushkina and Izmodenov, Astron. Let. 2009)

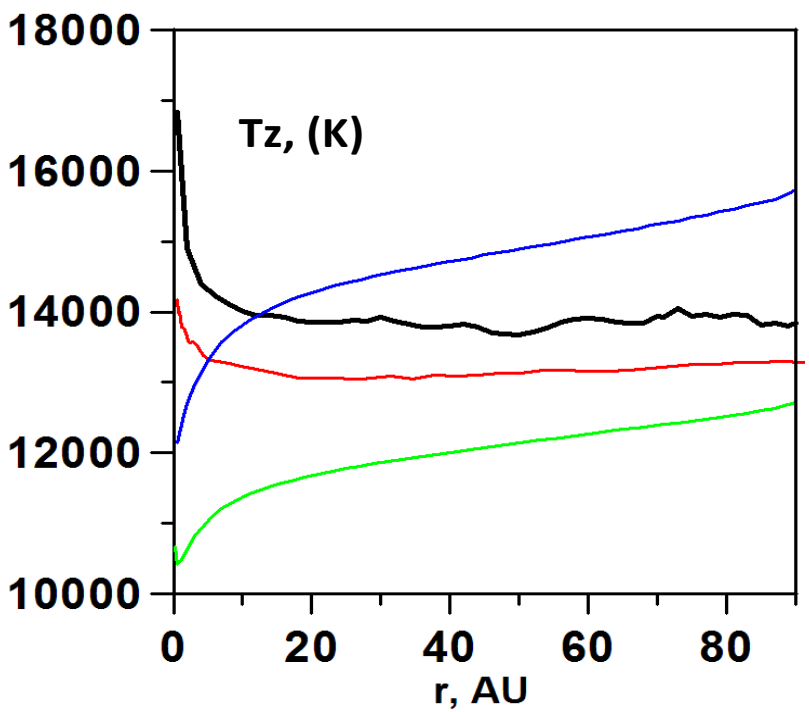
<u>Two-step procedure (commonly accepted):</u>

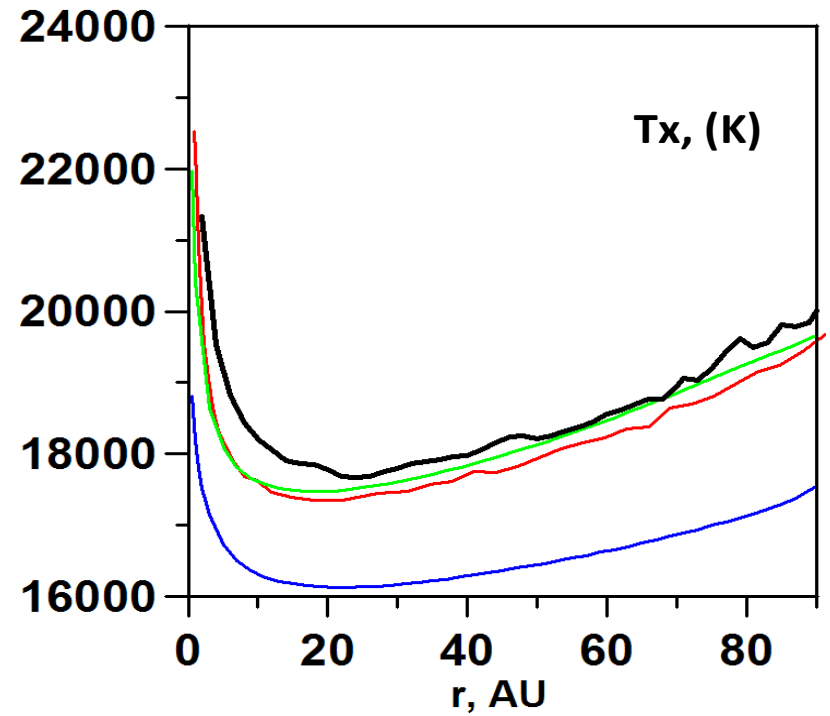
1. H atom distribution obtained at the TS from global self-consisten model;
2. detailed modeling of H atom properties inside the supersonic solar wind (so-called «advanced» hot model):

$$\frac{\partial f(\mathbf{r},\mathbf{w},t)}{\partial t}+\mathbf{w}\cdot\frac{\partial f(\mathbf{r},\mathbf{w},t)}{\partial \mathbf{r}}+\mathbf{F}(w_r,t,\theta)\cdot\frac{\partial f(\mathbf{r},\mathbf{w},t)}{\partial \mathbf{w}}+f(\mathbf{r},\mathbf{w},t)\cdot\frac{\partial \mathbf{F}(w_r,t,\theta)}{\partial \mathbf{w}}=-\beta(r,t,\theta)\cdot f(\mathbf{r},\mathbf{w},t)$$

<u>Boundary conditions from step 1:</u> a) Maxwellian approximation; b) function that includes all second moments (Katushkina's model); c) table function directly obtained by Monte-Carlo

Secondary interstellar atoms (population 3)
upwind direction (θ =0)





Classical hot model

Our model: advanced model with analytical formula for the boundary condition

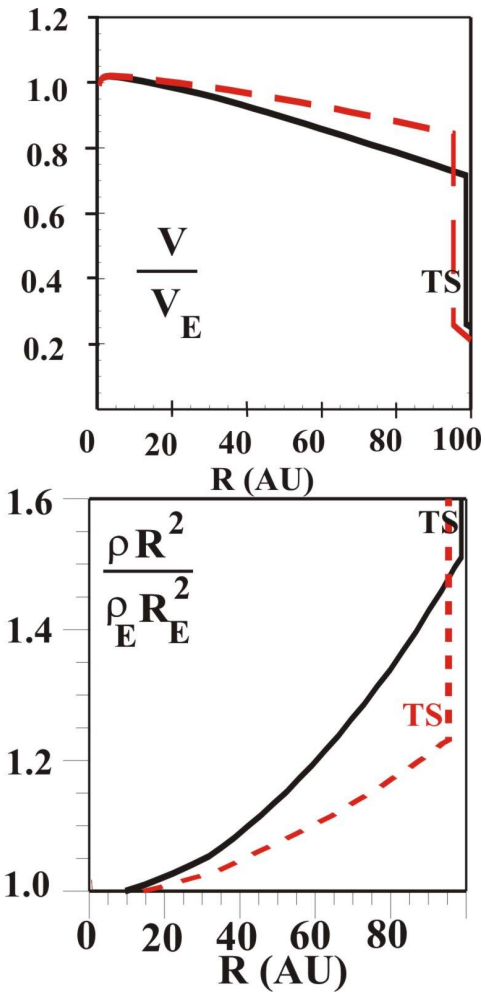
Baranov-Malama model

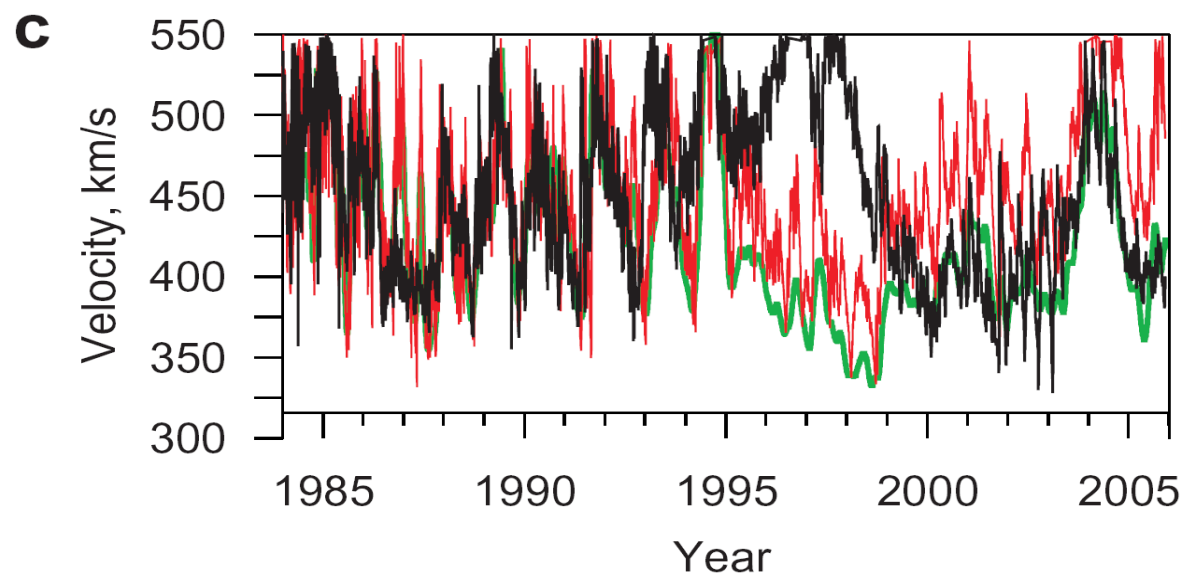
Our model-2: advanced model with realistic (from Monte-Carlo) function at boundary sphere

<u>Conclusion of this study:</u> Monte-Carlo with splitting of trajectories is more effective than the two-step procedure

How does charge exchange modify the plasma flow...

in the supersonic solar wind?





Time-dependent 6D kinetic-gasdynamic model vs. V2 data (Izmodenov et al, 2008)

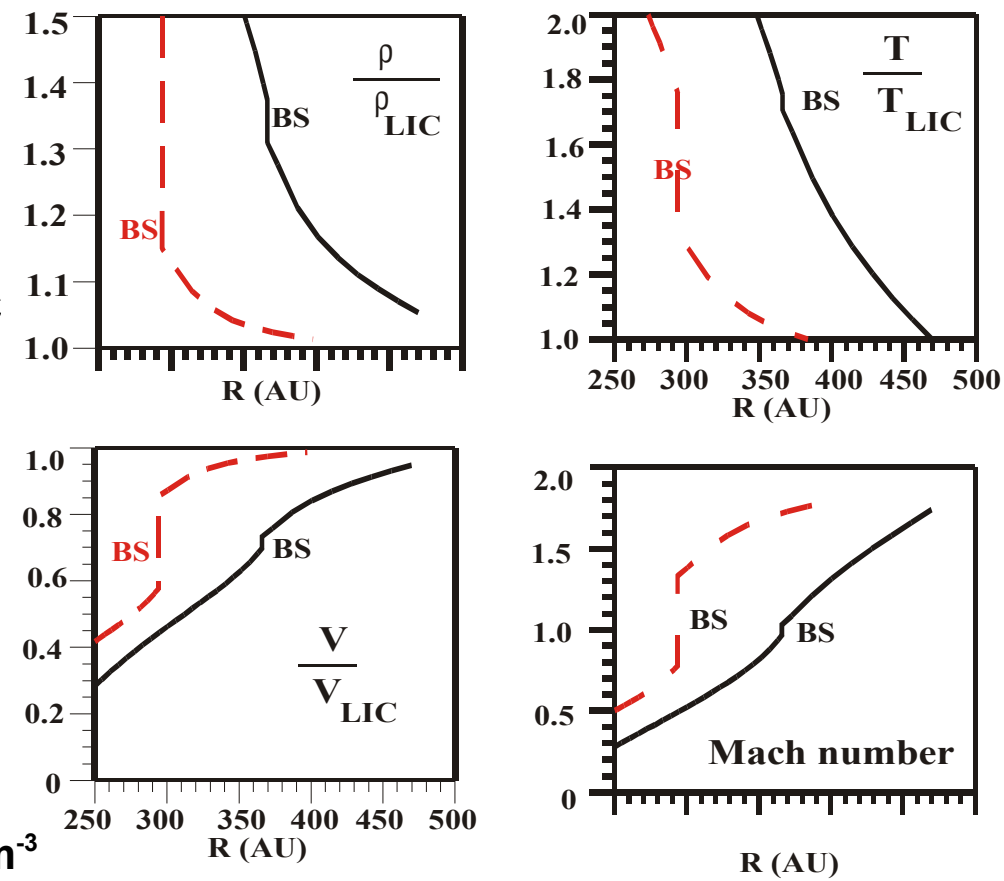
Red dashed: $n_{p,LIC}$=0.04 cm^{-3} , $n_{H,LIC}$= 0.2 cm^{-3}

Black solid: $n_{p,LIC}$=0.10 cm^{-3} , $n_{H,LIC}$= 0.2 cm^{-3}

(Izmodenov, 2000)

How does charge exchange modify the plasma flow in the intertsellar wind?

Interstellar supersonic flow is modified by charge exchange with heliospheric ENAs



Red dashed: $n_{p,LIC}$=0.04 cm^{-3} , $n_{H,LIC}$= 0.2 cm^{-3}

Black solid: $n_{p,LIC}$=0.10 cm^{-3} , $n_{H,LIC}$= 0.2 cm^{-3}

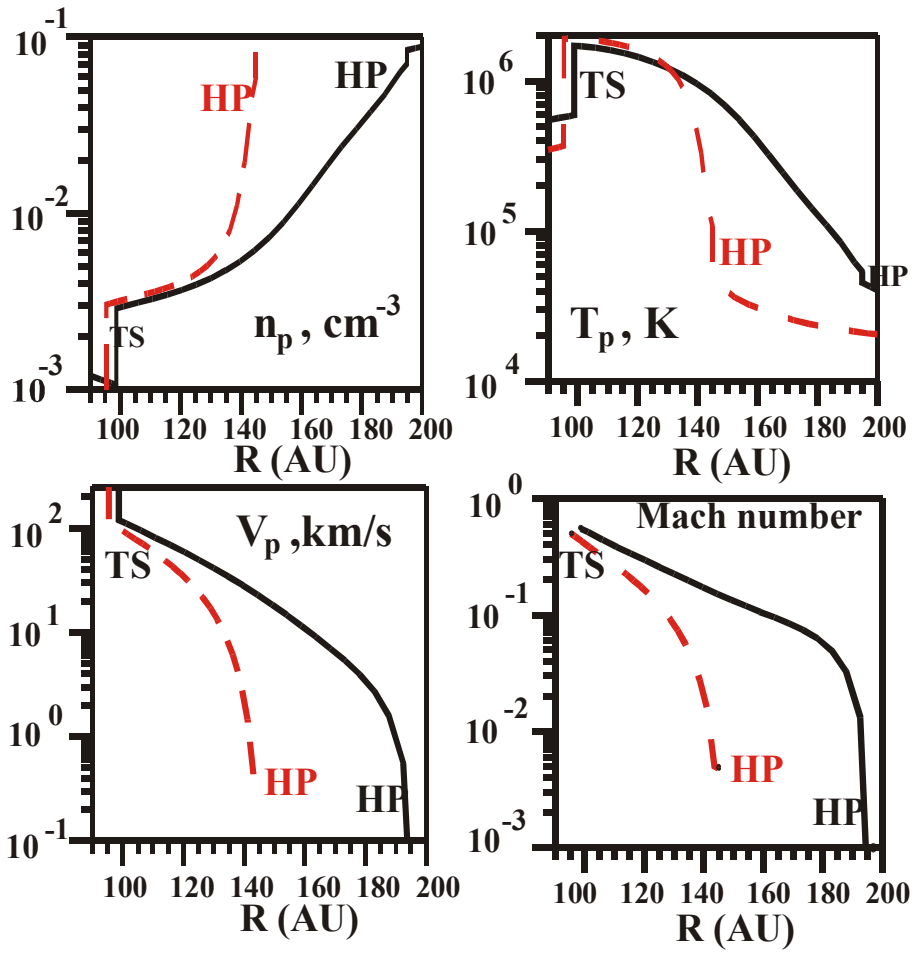
(Izmodenov, 2000)

How does charge exchange modify the plasma flow in the inner heliosheath?

(region between the termination shock and the heliopause)

<u>Results of numerical modeling:</u>

Due to charge exchange and (possibly) electron impact ionization the jump of parameters at the HP becomes smaller.



Red dashed: $n_{p,LIC}$=0.04 cm^{-3} , $n_{H,LIC}$= 0.2 cm^{-3}

Black solid: $n_{p,LIC}$=0.10 cm^{-3} , $n_{H,LIC}$= 0.2 cm^{-3}

(Izmodenov, 2000)

The flow in the vicinity of the stagnation point has been studied analytically (Belov, Astron. Let, accepted, 2009)

<u>Conclusion :</u> there are no jumps of plasma parameters at the stagnation point, there at this point the HP is not discontinuity — there is a transition layer.
This is the effect of charge exchange.

The HP could be a discontinuity outside of the stagnation point

Belov & Ruderman (2009) have 2D analytical solution in the vicinity of the stagnation point.

The heliospheric interface is extended in the tail direction

Alexashov & Izmodenov 2003

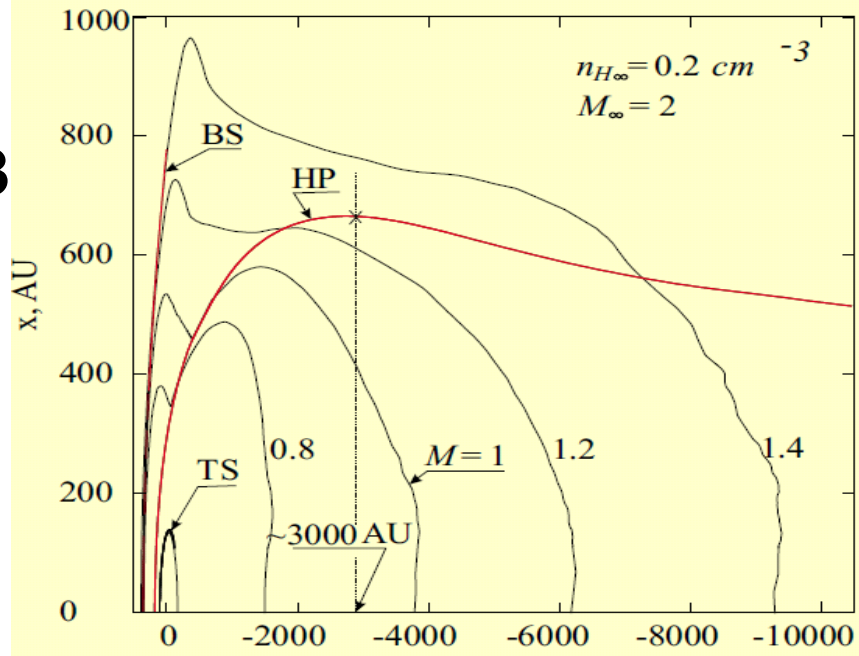
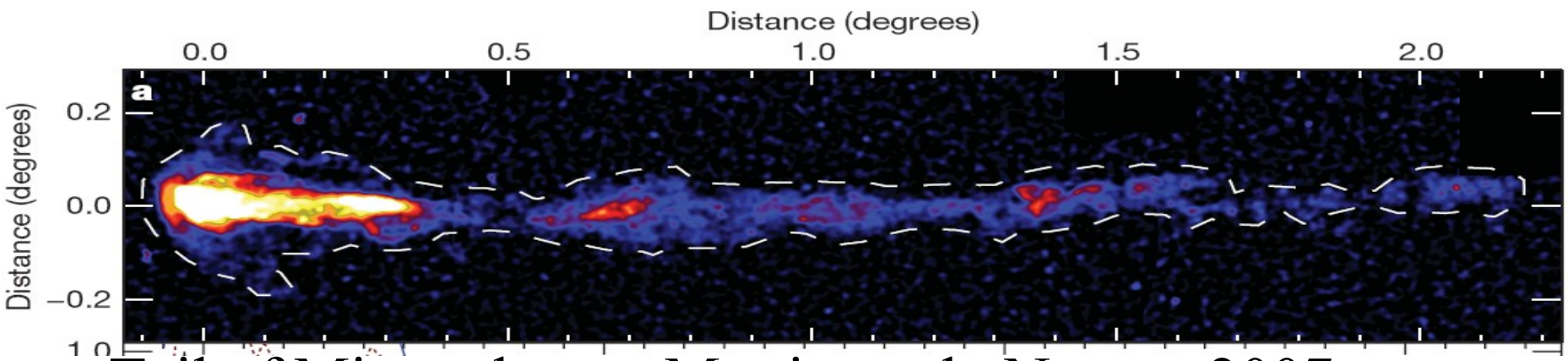


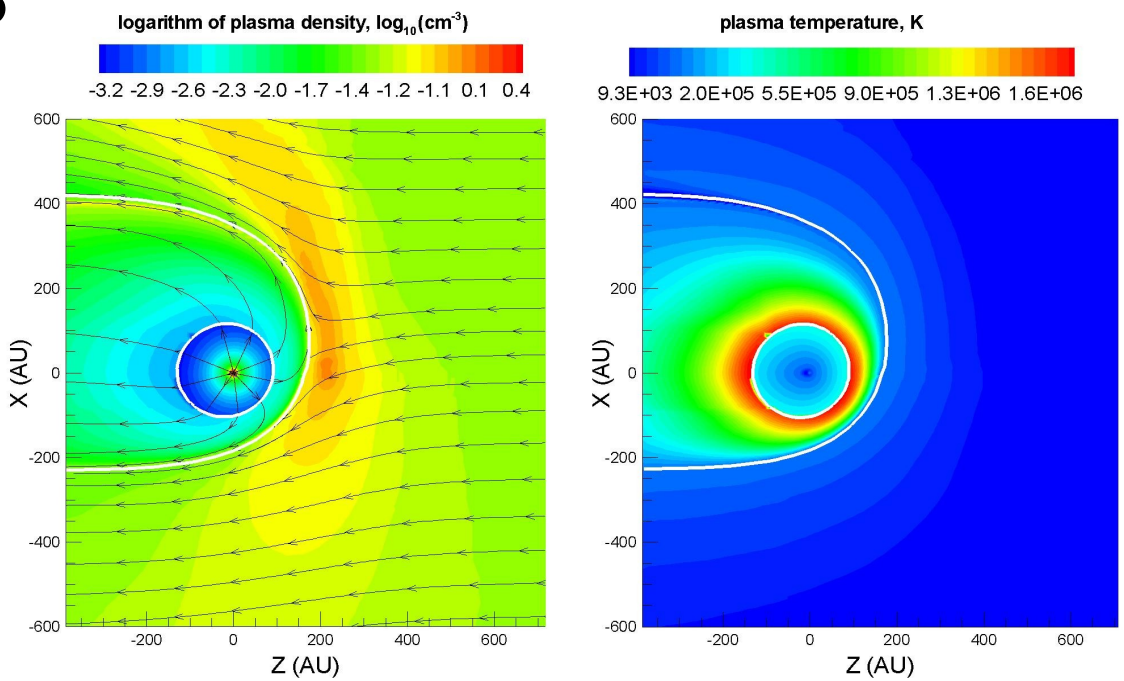
Figure 3. Isolines of Mach number M. It is seen that on the distances more than 4000 AU into the heliotail direction the solar wind flow is supersonic. The Mach number increases with increase of the heliocentric distance and approaches its interstellar number.



Tail of Mira-sphere, Martin et al., Nature, 2007

Shape of the heliopause of modified by interstellar magnetic field

RESULTS OF MODEL WITH B_{LIC}=4.375μG and angle ($B_{LIC}V_{LIC}$)=15°



M = 1.97

M_A = 0.678

M_{Z+} = 0.675

Distributions are shown in ($\mathbf{B}_{LIC}\mathbf{V}_{LIC}$) plane

The bow shock is absent since (M_A<1, M_{Z+}<1).

Distances to TS in Voyager 1 and Voyager 2 directions

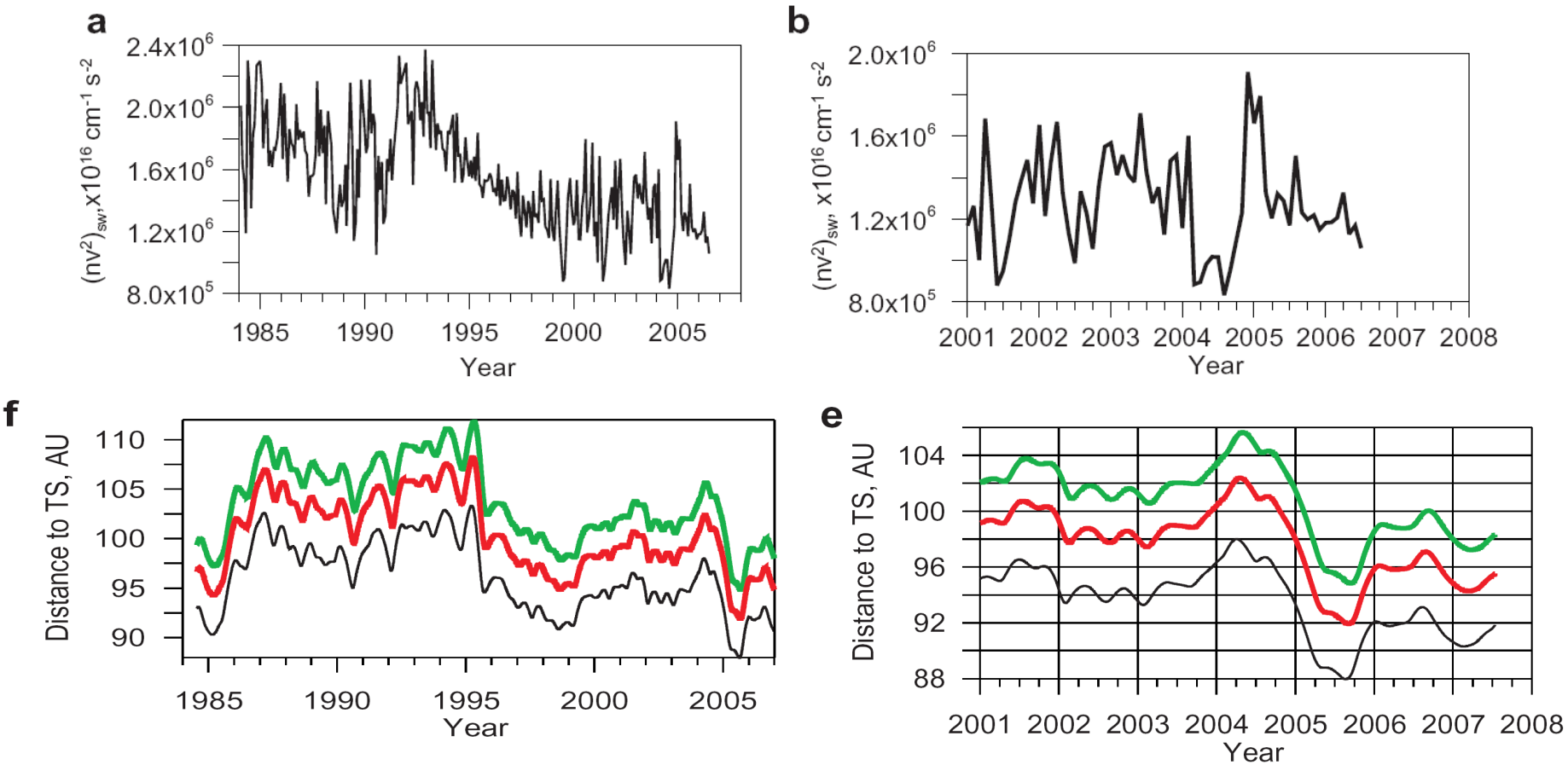
Distance to the termination shock in V1 and V2 directions (results of stationary models)

B_{LIC}, μG	0	2.5	2.5	5.0	4.375	4.375	2.5	2.5	1.25	2.5	2.5
α (B_{LIC}, V_{LIC})		0	15	15	15	20	30	45	45	60	90
cross section	M&T	M&T	M&T	M&T	Steb.	Steb	M&T	M&T	M&T	M&T	M&T
V1	99	100.9	98.4	93.2	97.0	94.3	92.5	86.8	93.1	85.5	84.1
V2	104	104.7	99.2	87.3	91.5	87.4	92.6	87.5	95.6	87.2	88.2

Distances to the termination shock in V1 and V2 directions (time-dependent correction is made; NEXT SLIDE)

B_{LIC}	0	2.5	2.5	5.0	4.375	4.375	2.5	2.5	1.25	2.5	2.5
α(B_{LIC}, V_{LIC})		0	15	15	15	20	30	45	45	60	90
cross section	M&T	M&T	M&T	M&T	Steb.	Steb	M&T	M&T	M&T	M&T	M&T
V1	98	99.9	97.4	92.2	96.0	93.3	91.5	85.8	92.1	84.5	83.1
V2	98	99.7	94.2	82.3	86.5	82.4	87.6	82.5	90.6	82.2	83.2

Distance to the TS



Izmodenov, Malama, Ruderman, Adv. Space Res., 2008

Conclusion on the 3D parametric studies (Izmodenov et al., Sp.Sci.Rev.,2008)

- Solution with B_{LIC} ~ 4.5-5 μG and angle $\alpha(\mathbf{B}_{LIC}, \mathbf{V}_{LIC})$= 15-20 deg. is in agreement with both 1) V1 and V2 crossings of the TS; 2) deflection of H atom direction;

- Role of charge exchange is quantitatively important and Lindsay and Stebbings (2005) cross section seems to be more appropriate (i.e. results of the model better corresponds to data); This is semi-intuitive conclusion: additional numerical proofs are needed (and they are on the way).

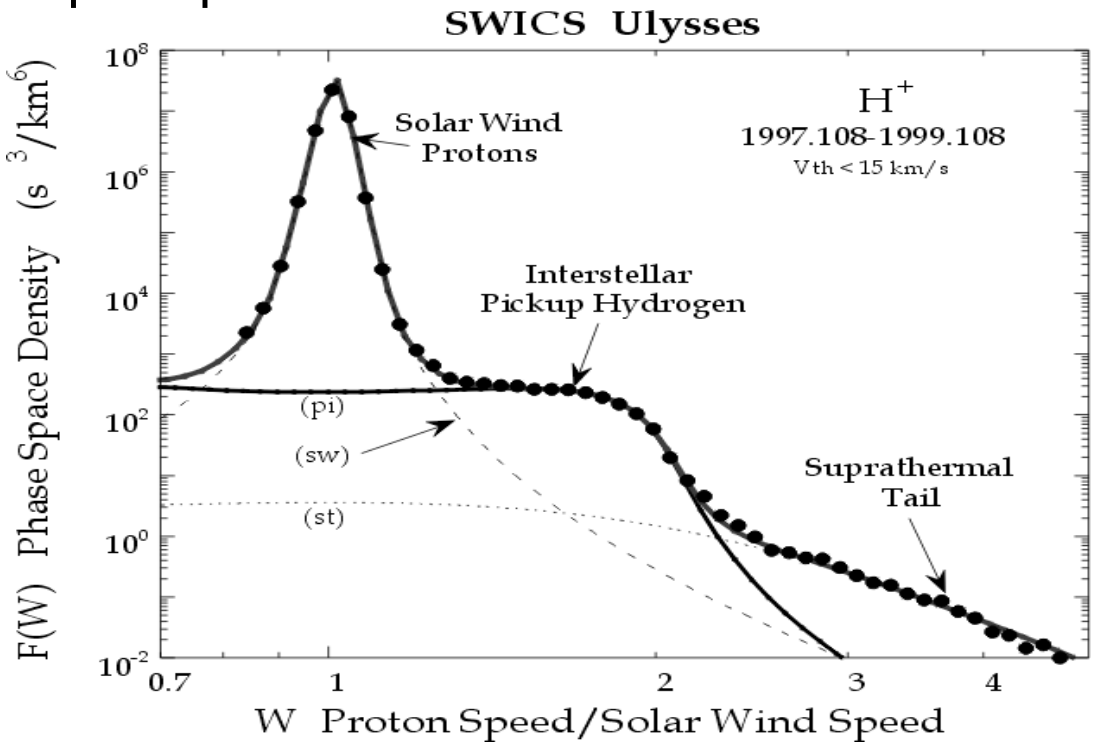
- Interstellar oxygen is less deflected as compared with hydrogen.

An assumption of the most of global models of the heliospheric interface:

one-fluid approach for the charged components in the solar wind (electrons, protons, solar wind alpha particles and <u>pickup ions</u>)

<u>From observations:</u>

- Pickup ions are thermally decoupled from solar wind protons;
- Velocity distribution of pickup ions is not Maxwellian.



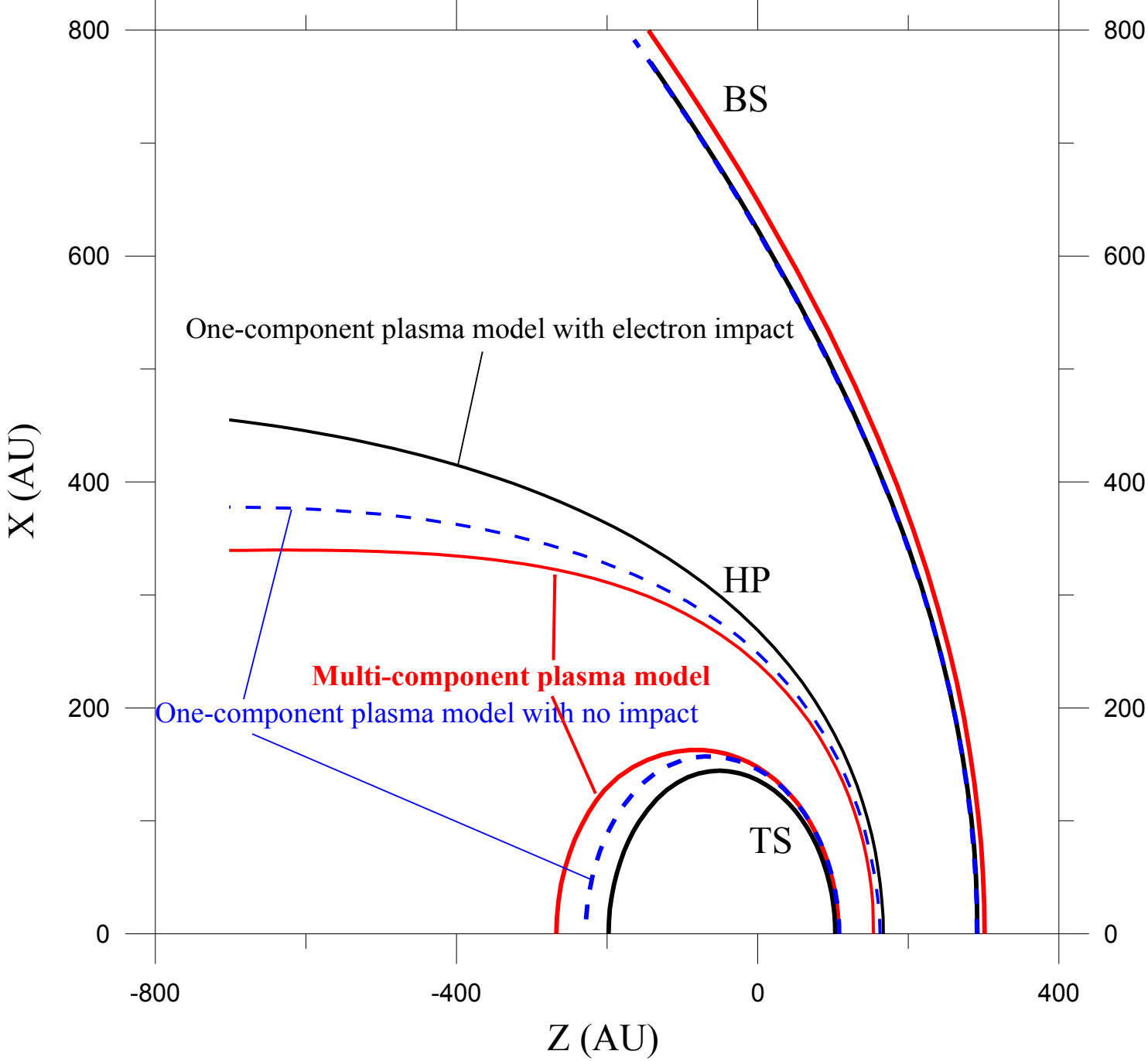
Model with non-equilibrium heliospheric plasma: kinetic description of pickups

• Kinetic description of interstellar H-atoms;
• Assumption: All charged components (solar and pickup protons, electrons, alpha particles) are **co-moving**;
• Approach is based on mass, momentum and energy balance for sum of all charged components;
•All protons in the heliosphere are divided into several sorts depending on their energy and their origin;
• It is assumed that proton velocity distribution functions are **isotropic** (in the s.w. rest frame) for all sorts and it is Maxwellian for the coldest sort (which includes original solar protons);
• Kinetic description of pickup protons (Fokker-Planck equation):

$$\frac{\partial f^*_{pui}}{\partial t} + \vec{u} \cdot \frac{\partial f^*_{pui}}{\partial \vec{r}} = \frac{1}{w^2}\frac{\partial}{\partial w}\left(w^2 D \frac{\partial f^*_{pui}}{\partial w}\right) + \frac{w}{3}\frac{\partial f^*_{pui}}{\partial w} div(\vec{u}) + S(\vec{r}, w),$$

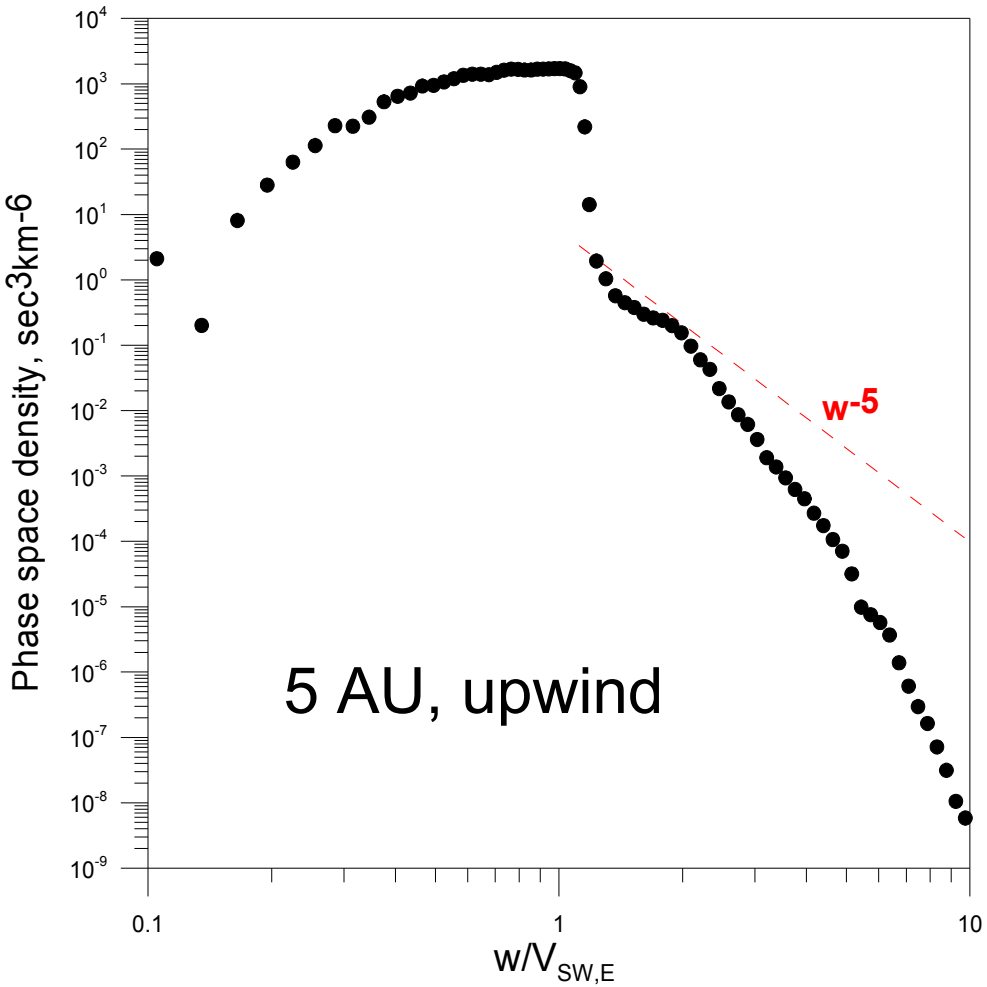
S – source of pickup protons; *w*- thermal velocity of pickups, *D*- diffusion coefficient in velocity space;
• Heat transfer equation for electron component.

•**THE SOLAR WND PROTONS ARE SUPERSONIC AFTER TS**



Multi-component:
HP ~12 AU closer;
TS ~ 5 AU away
as compared with
Baranov & Malama
-model

Results of the model with D=0 (no stochastic acceleration)



Black dots: Model results with D=0; the suprathermal tail is due to ENAs from the heliosheath

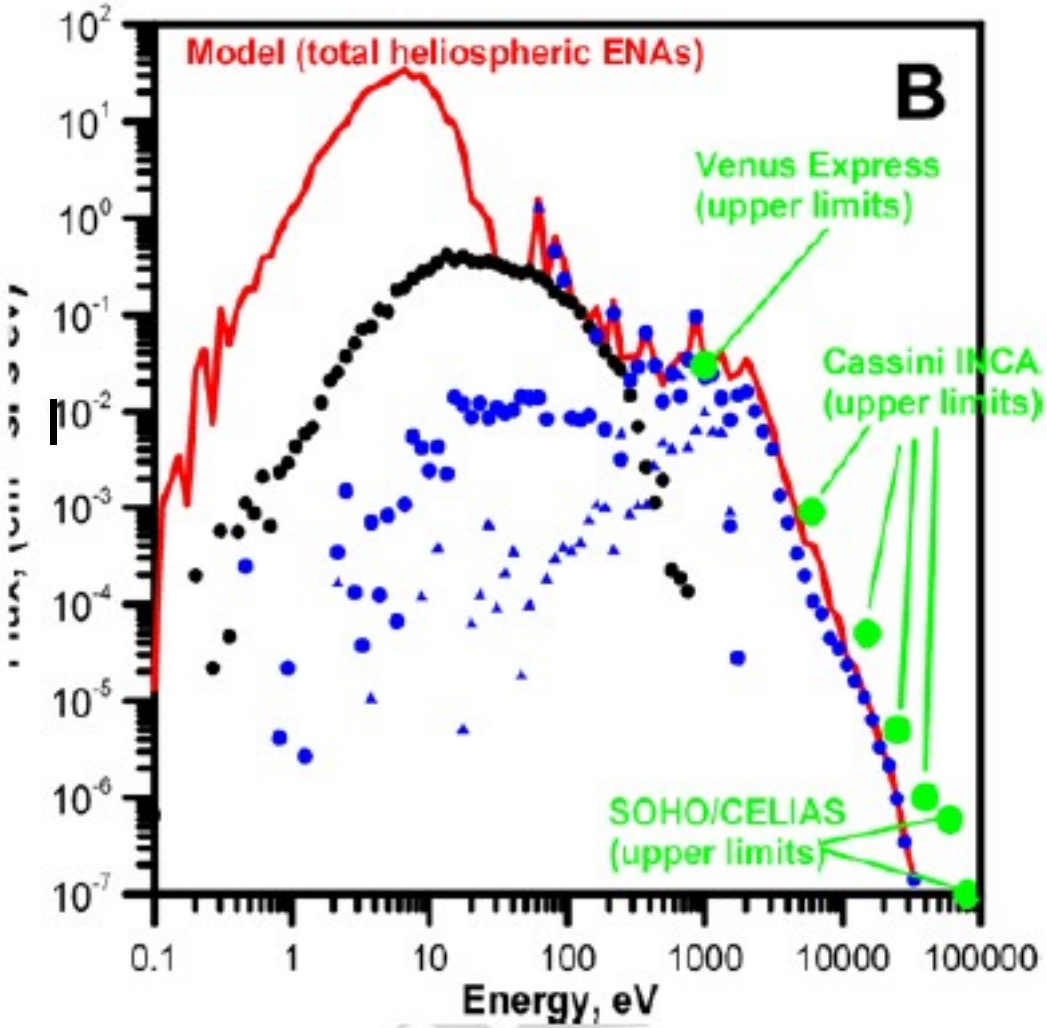
Dashed red curve: observed spectra from Fisk and Gloeckler (2007).

- Good **agreement** for intensity of suprathermal tail at $w/V_{sw,E} \sim 1.2$

This is an indication of primary role of heliospheric ENA in the tail formation.

- **Disagreement** of the spectral indexes of theory and data.

All considerations for quite solar wind



Izmodenov et al., 2009

Soon will be confirmed or invalidated by IBEX data

(*curves 1*), and in accordance with the equilibrium plasma model (*curves 2*). **B** Fluxes of H atoms at 1 AU calculated with pickup proton non-equilibrium model: total fluxes of all heliospheric ENAs (*solid curve*), ENAs originated in the inner heliosheath from solar wind protons (*black dots*), ENAs originated in the inner heliosheath from pickup protons (*blue triangles*), ENAs originated in the outer heliosheath from pickup protons (*blue dots*). Upper limits of heliospheric ENA fluxes measured by SOHO/CELIAS, Cassini/INCA and Venus Express are shown by the green dots

CONCLUSIONS

1. Multi-component nature of the solar wind interaction with the local interstellar medium requires to solve different type of equations (MHD, kinetic, Fokker-Planck, diffusion equation, etc.) simultaneously and self-consistently.

2. Role of the interstellar neutral component and charge exchange is very important in the heliospheric interface. Due to their large mean free path interstellar neutral provide transfer of momentum and energy from one regions of the heliosphere to other.

3. Very soon Interstellar Boundary Explore (IBEX) will provide new observational constraints on the models of the heliosphere interface. These measurements may change of current paradigm of nature of the heliospheric boundaries.