

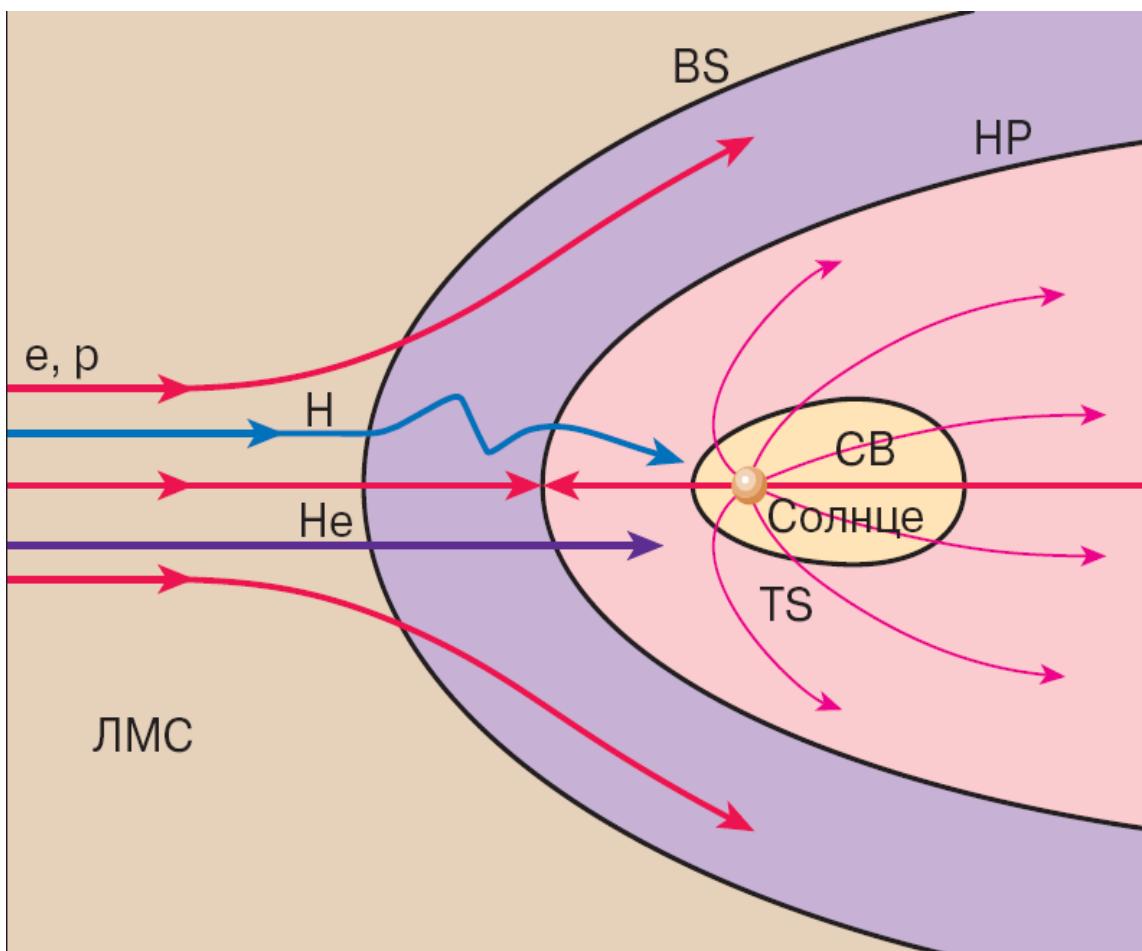
Гелиосферный ударный слой: межзвездное магнитное поле, захваченные протоны и гелиосферные ЭНА

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План:

1. Понятие гелиосферного ударного слоя.
2. Роль межзвездного магнитного поля и анализ факта пересечения гелиосферной ударной волны КА Voyager 1 и 2
3. О природе высоко-энергичных хвостов в функции распределения протонов в гелиосфере.
4. Энергичные нейтралы гелиосферного происхождения

Объект исследования — область взаимодействия солнечного ветра с межзвездной средой (гелиосферный ударный слой или гелиосф. интерфейс)



BS – головная ударная волна, HP – гелиопауза, отделяющая солнечного ветра от плазму межзвездной среды, TS – ударная волна торможения солнечного ветра. Синей линией показана траектория атомов водорода, на которую воздействуют процессы перезарядки, а фиолетовой линией – траектория атомов гелия, на которую процессы перезарядки практически не оказывают влияния.

1. 3D MHD-kinetic model: new self -consistent solutions; Role of the charge exchange cross-section;

High interest is generated by:

- 1) Voyager 1 crossing the TS at 94 AU in Dec 2004;
Voyager 2 crossing the TS at 84 in Aug-Sept 2007

(comparison allows to measure distortion of the heliosphere);

- 2) Recent SOHO/SWAN measurements (deflection of H atom flow)

Several papers: Pogorelov et al.(2005, 2006, 2007,2008),
Opher et al.(2006, 2007,2008),
Izmodenov et al. (A&A, 2005),
Izmodenov & Alexashov (IGPP Conf. Proc., 2006)

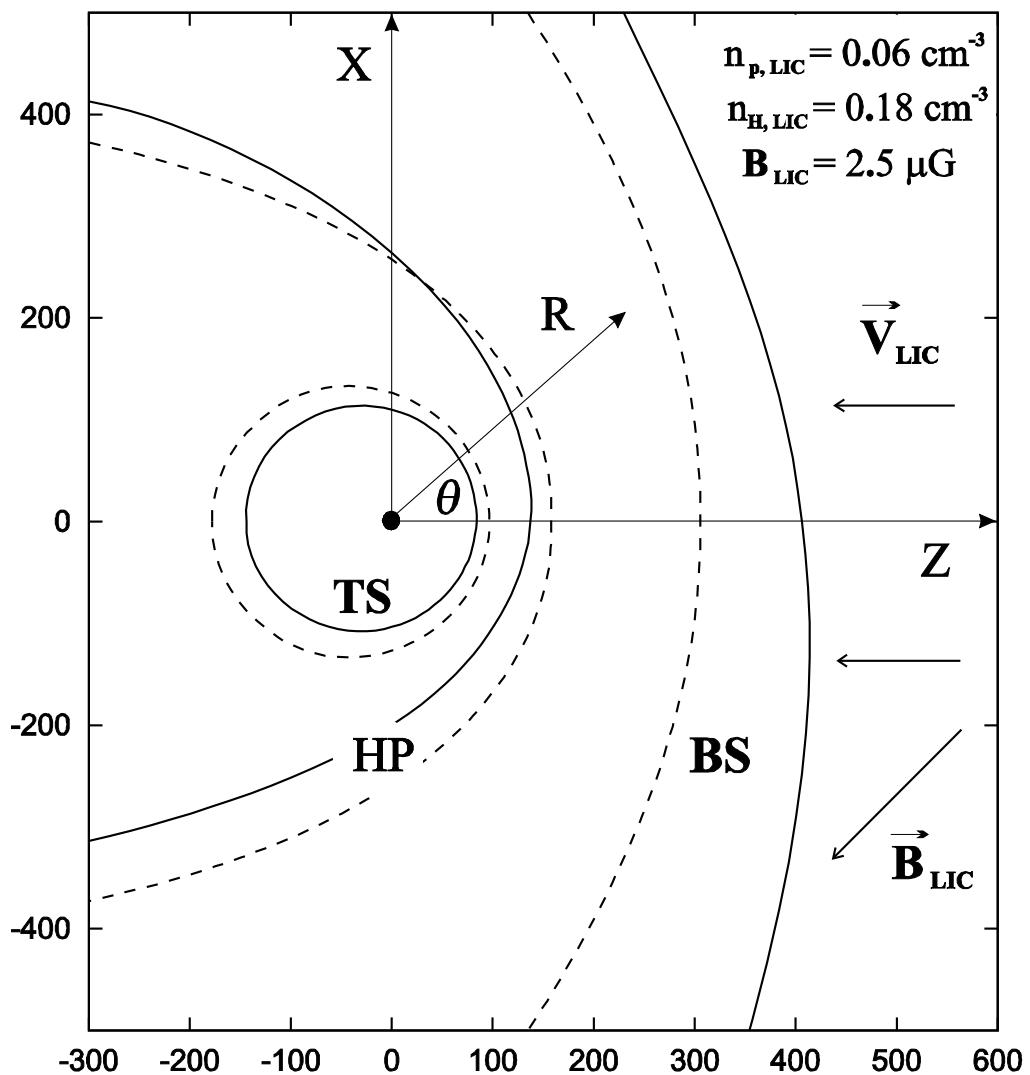
- В Izmodenov et al. (2005) разработана 3D кинетико- МГД модель гелиосферного интерфейса;
- Исследовано влияние межзвездного магнитного поля на структуру гелиосферного интерфейса

Постановка задачи:

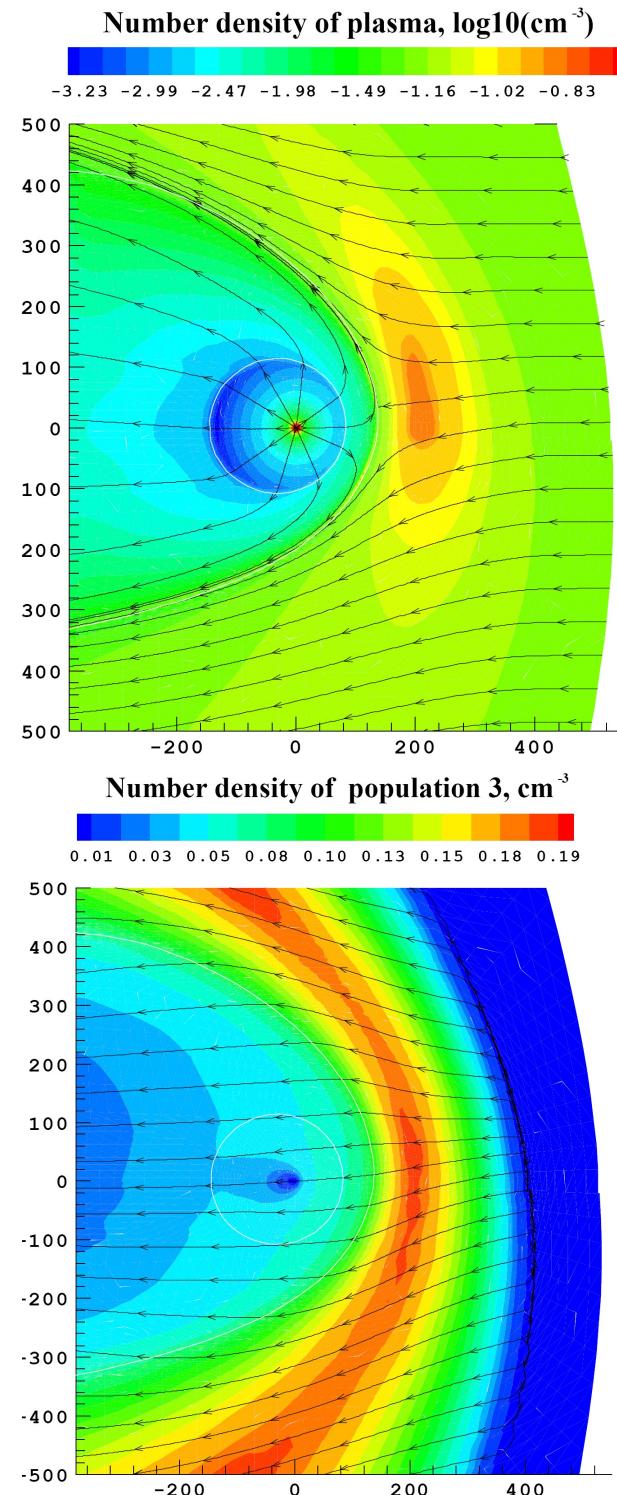
- Уравнения МГД с правыми частями в которых учитываются процессы перезарядки, ионизации электронным ударом, фотоионизации, солнечной гравитации и силы радиационного давления + 6D кинетическое уравнение для атомов водорода.

Границные условия:

- на орбите Земли - параметры солнечного ветра;
- в локальной межзвездной среде:
 V_{LIC} , T_{LIC} , $n(H, LIC)$, $n(p, LIC)$, $B(LIC)$, α — угол между $V(LIC)$ и $B(LIC)$



Izmodenov et al., A&A Let. 2005



Distances to TS in Voyager 1 and Voyager 2 directions

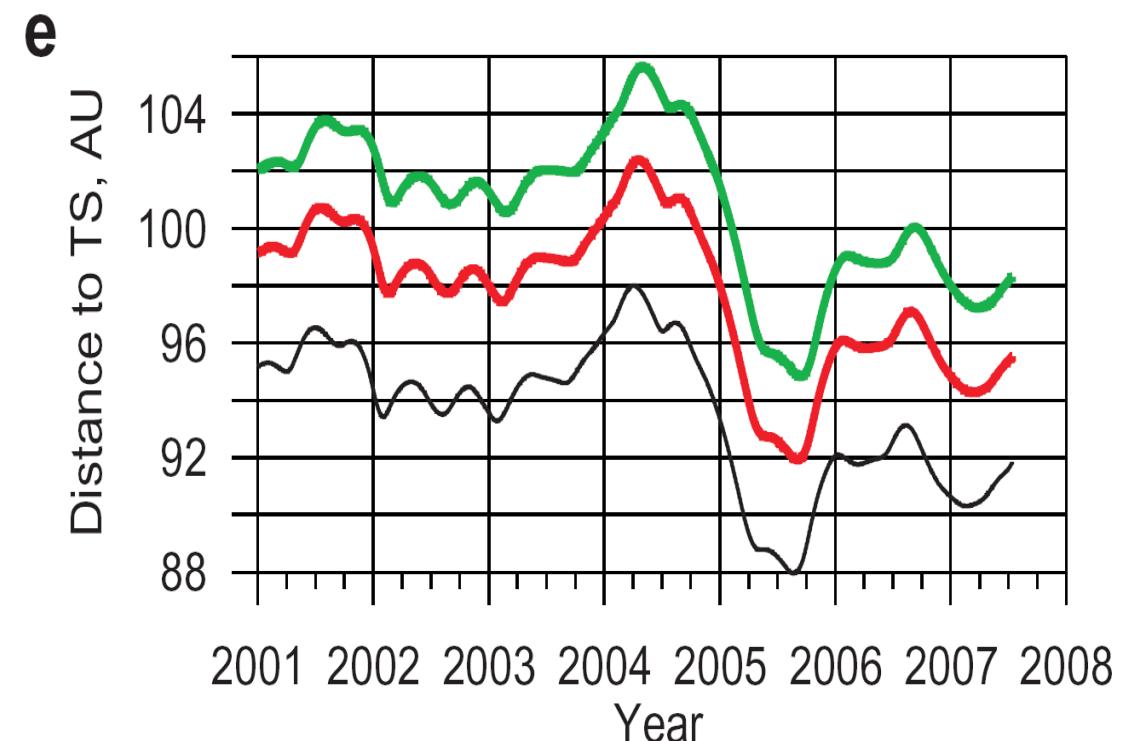
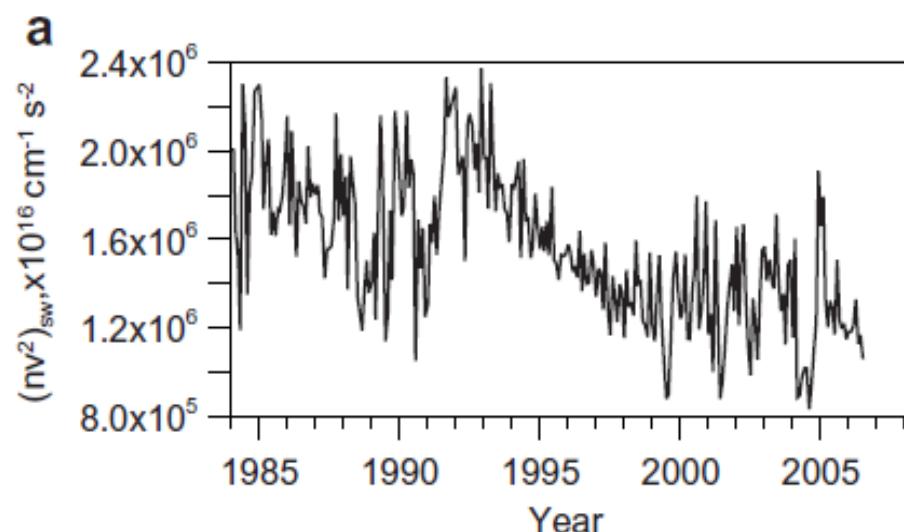
Distance to the termination shock in V1 and V2 directions (results of stationary models)

$B_{LIC}, \mu G$	0	2.5	2.5	5.0	4.375	4.375	2.5	2.5	1.25	2.5	2.5
$\alpha(B_{LIC}, V_{LIC})$		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

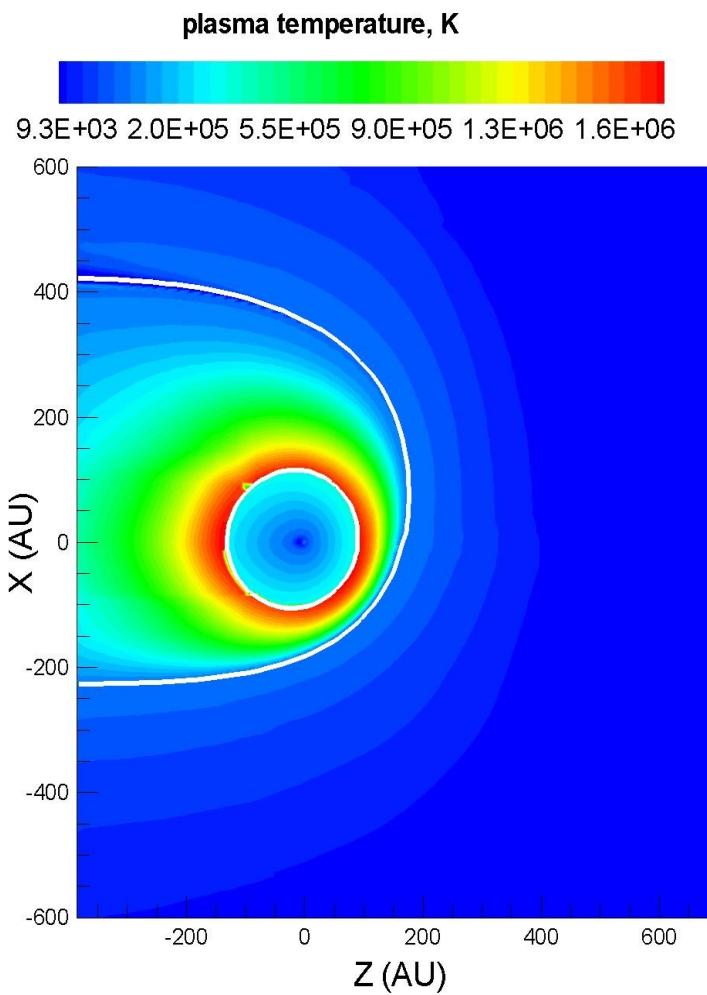
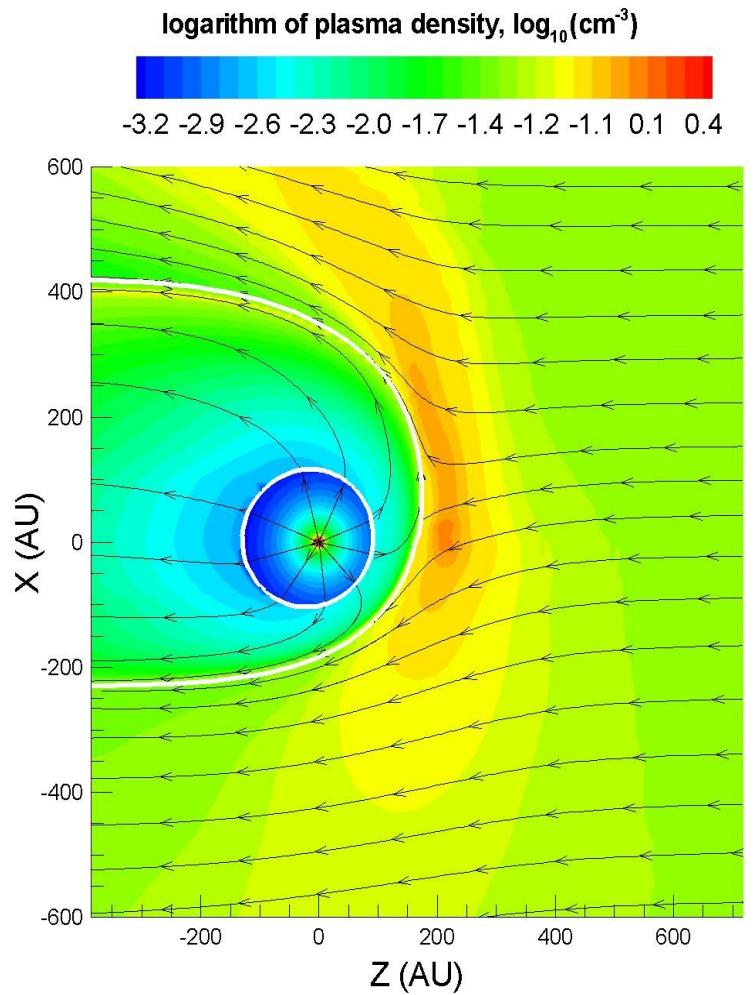
Distances to the termination shock in V1 and V2 directions (time-dependent correction is made)

B_{LIC}	0	2.5	2.5	5.0	4.375	4.375	2.5	2.5	1.25	2.5	2.5
$\alpha(B_{LIC}, V_{LIC})$		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

Положение гелиосферной ударной волны в зависимости от солнечного цикла (Izmodenov et al.. 2008)



RESULTS OF MODEL WITH $B_{\text{LIC}}=4.375\mu\text{G}$ and angle $(B_{\text{LIC}}V_{\text{LIC}})=15^\circ$



$$M = 1.97$$

$$M_A = 0.678$$

$$M_{Z+} = 0.675$$

Distributions are shown in $(B_{\text{LIC}}V_{\text{LIC}})$ plane

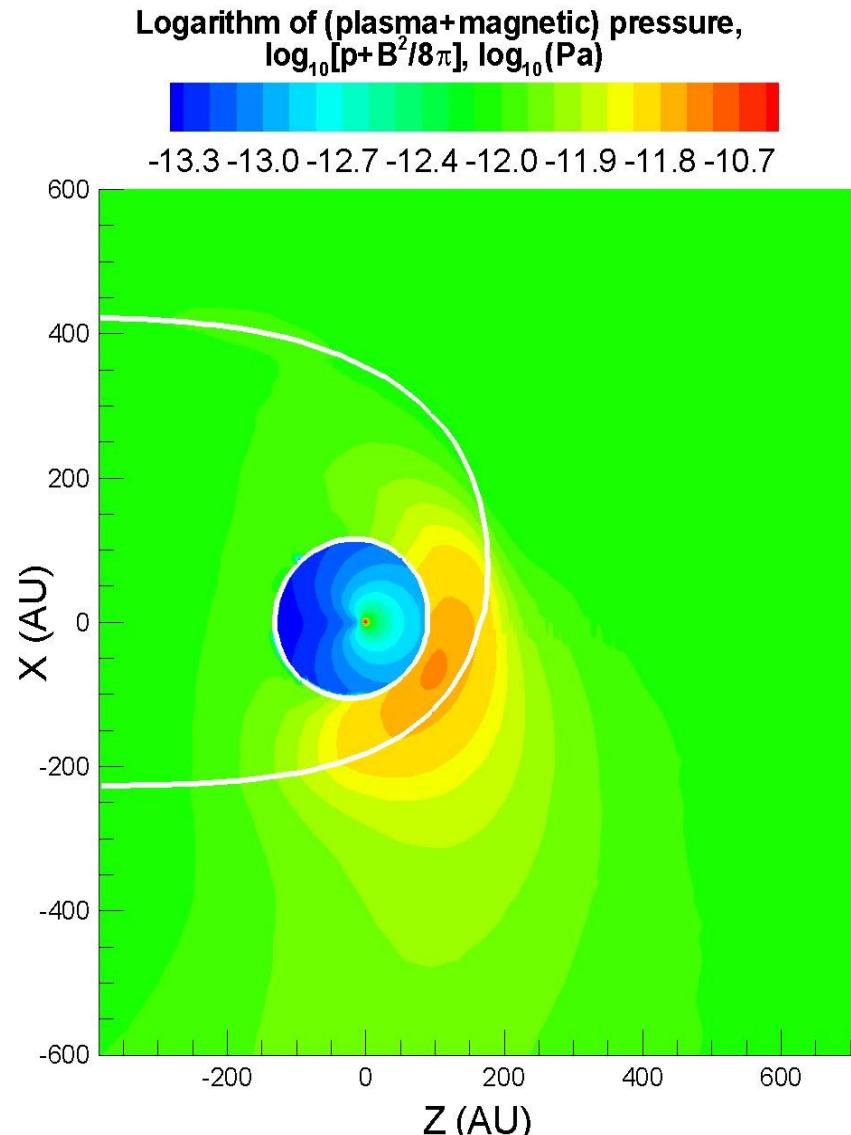
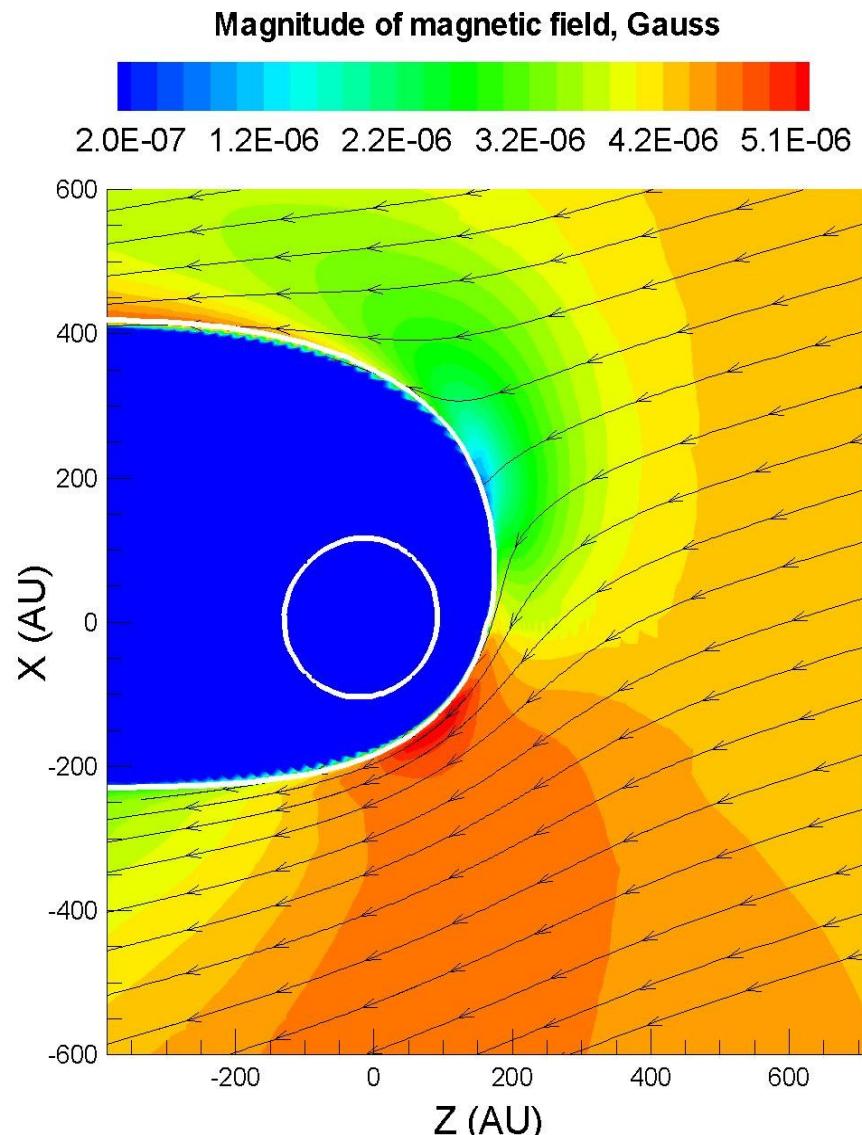
The bow shock is absent since $(M_A < 1, M_{Z+} < 1)$.

Charge exchange cross section (new):

$$\sigma(u) = (2.2835 \times 10^{-7} - 1.062 \times 10^{-8} \ln(u))^2 \quad (\text{Lindsay and Stebbings, 2005})$$

is different for previously (old) used. Effect of the new cross section is not negligible.

Magnetic field in the model with $B_{\text{LIC}}=4.375\mu\text{G}$ and angle $(B_{\text{LIC}}V_{\text{LIC}})=15^\circ$



Left: Magnitude of IsMF and field lines of IsMF that lead to asymmetry of the heliopause.

Right: Total (plasma + magnetic) pressure is conserved at the heliopause for self-consistent solution.

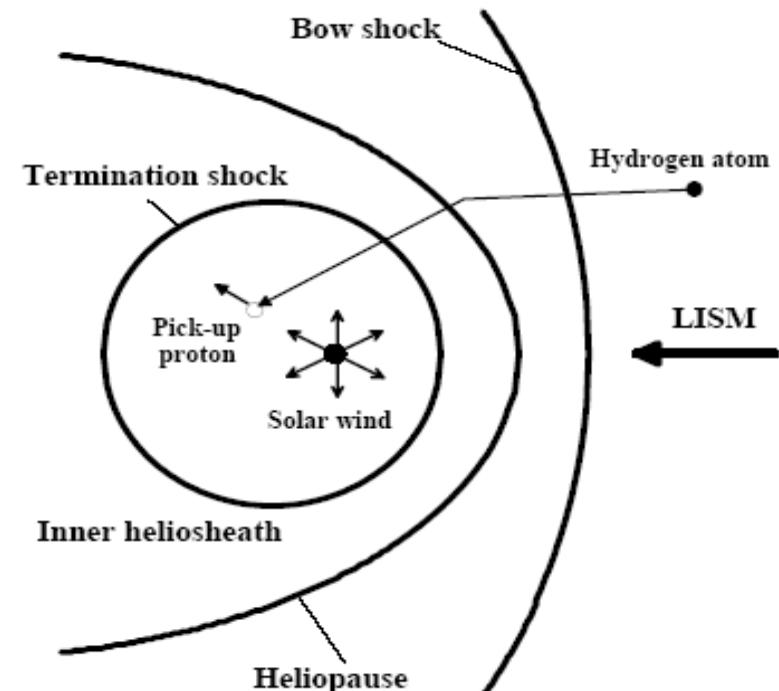
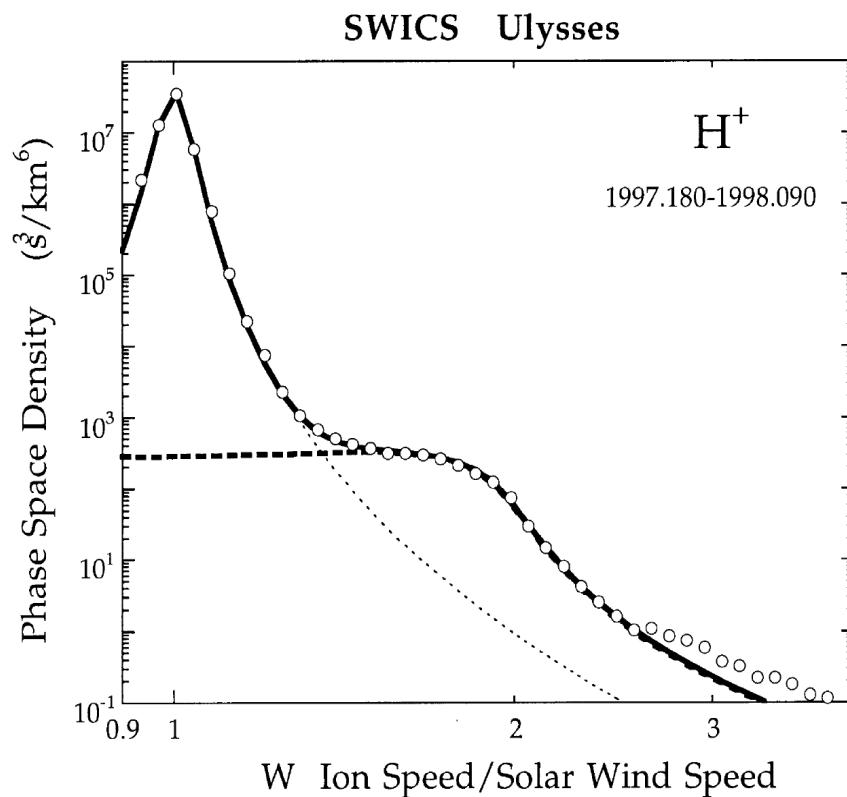
Conclusions on part 1:

- Solution with $B_{\text{LIC}} \sim 4.5\text{-}5 \mu\text{G}$ and angle $\alpha(\mathbf{B}_{\text{LIC}}, \mathbf{V}_{\text{LIC}}) = 15\text{-}20 \text{ deg.}$ 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 Stebbings et al. (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.

Модель с учетом неравновесного характера плаэмы: Кинетическое описание захваченных ионов; « w^{-5} »- хвосты

Цели исследования:

Попытка в рамках самосогласованной модели взаимодействия солнечного ветра с локальной межзвездной средой учесть и объяснить форму спектра высокоэнергичных хвостов захваченных протонов



Многокомпонентная модель (Malama, Izmodenov, Chalov, A&A, 2006) использовалась для того, чтобы:

1. Попытаться установить механизм образования хвостов со спектральным индексом -5 посредством стохастического ускорения на волнах, распространяющихся в солнечном ветре.

Модель Фиска-Глоесклера не учитывает источники и стоки захваченных ионов.

2. Проверить (количественно концепцию Чалова-Фара (Chalov&Fahr, 2003) — хвосты захваченных протонов в сверхзвуковом солнечном ветре формируются посредством ионизации энергичных нейтралов, проникающих из области внутреннего ударного слоя.
3. Предсказать потоки гелиосферных ЭНА, которые будут измеряться на КА IBEX

•Модель (Malama, Izmodenov, Chalov, 2006):

•Кинетический подход для описания межзвездных атомов

•(метод Монте-Карло для немаксвелловской функции

•распределения);

Все заряженные компоненты имеют одну скорость;

Все протоны разделены на несколько сортов в зависимости от их энергии и происхождения; предполагается, что функции распределения изотропны для всех сортов, и функция распределения является максвелловской для самой холодной компоненты;

Кинетическое уравнение для захваченных ионов (Уравнение Фоккера-Планка):

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

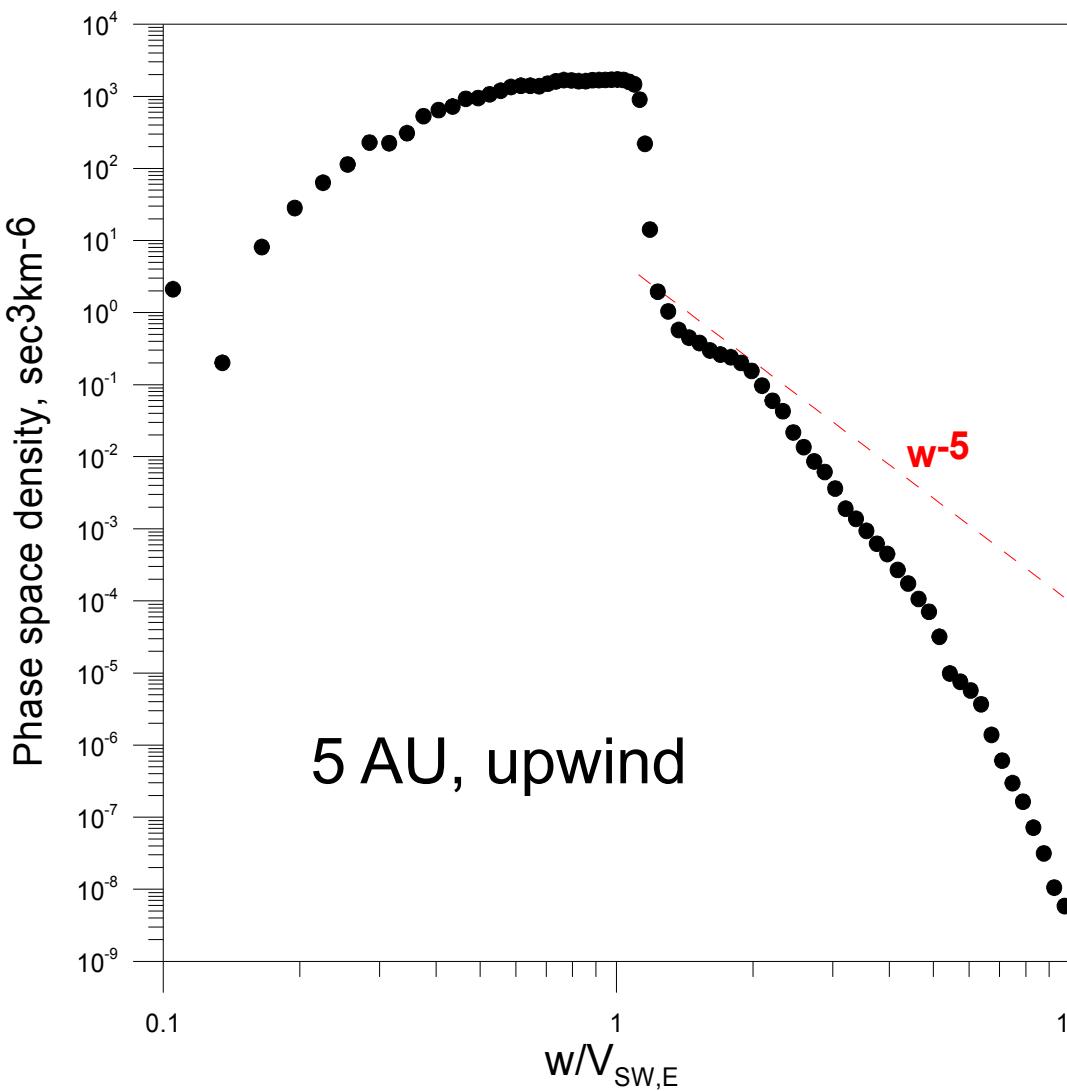
Уравнение притока тепла для электронов;

Баланс массы, импульса и энергии для всех компонент.

Отличие предыдущего (впервые в глобальных моделях гелиосферного ударного слоя) : учет межзвездных захваченных протонов, образующихся во внешнем части ударного слоя!

Протонная компонента солнечного ветра за гелиосферной ударной волной является в модели сверхзвуковой (что соответствует данным Вояджера-2).

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

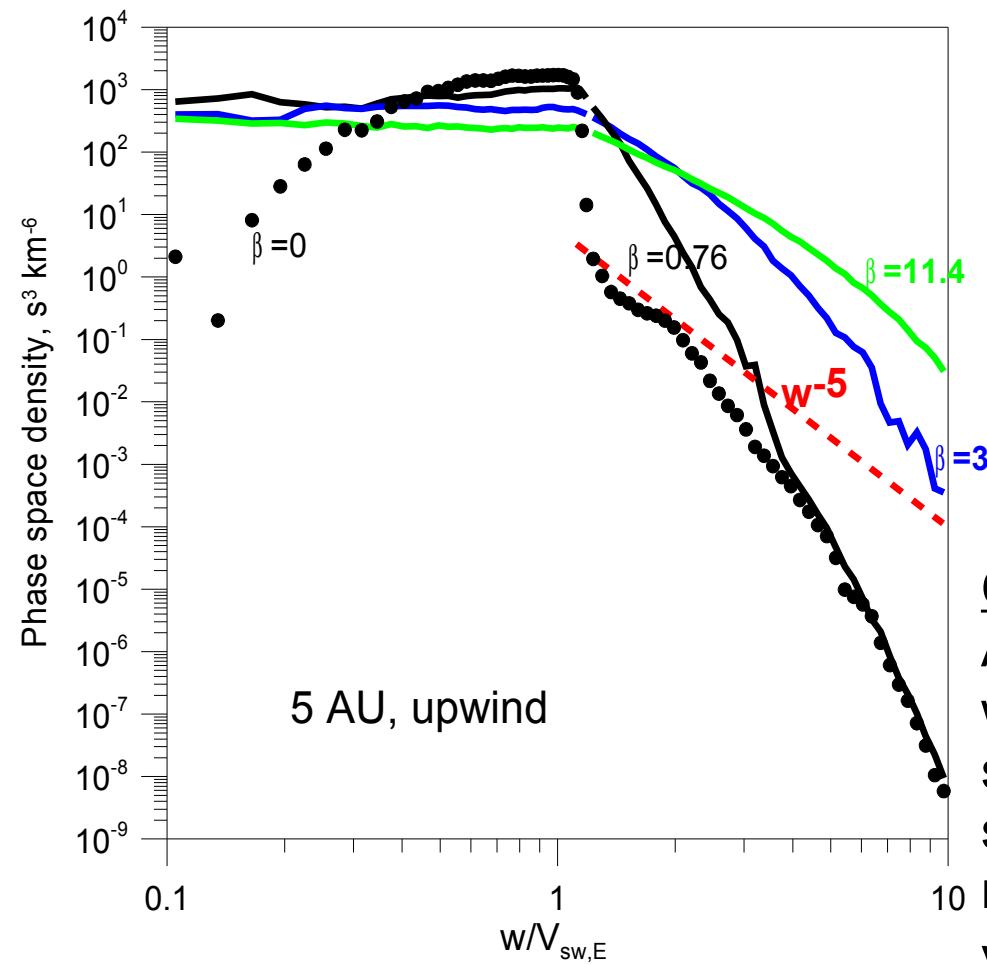
Dashed red curve: observed spectra from Fisk and Gloeckler (2007).

- 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.

Possible mechanisms to change the spectral index in the model

- Stochastic acceleration in the supersonic solar wind by Alfvénic or compressional turbulences;
- Stochastic acceleration in the inner heliosheath by Alfvénic or compressional turbulences;
- Adiabatic acceleration due to regular negative divergence in the inner heliosheath [exists in basic ($D=0$) model of Malama et al. (2006)]

Acceleration in the supersonic solar wind by Alfvénic turbulence

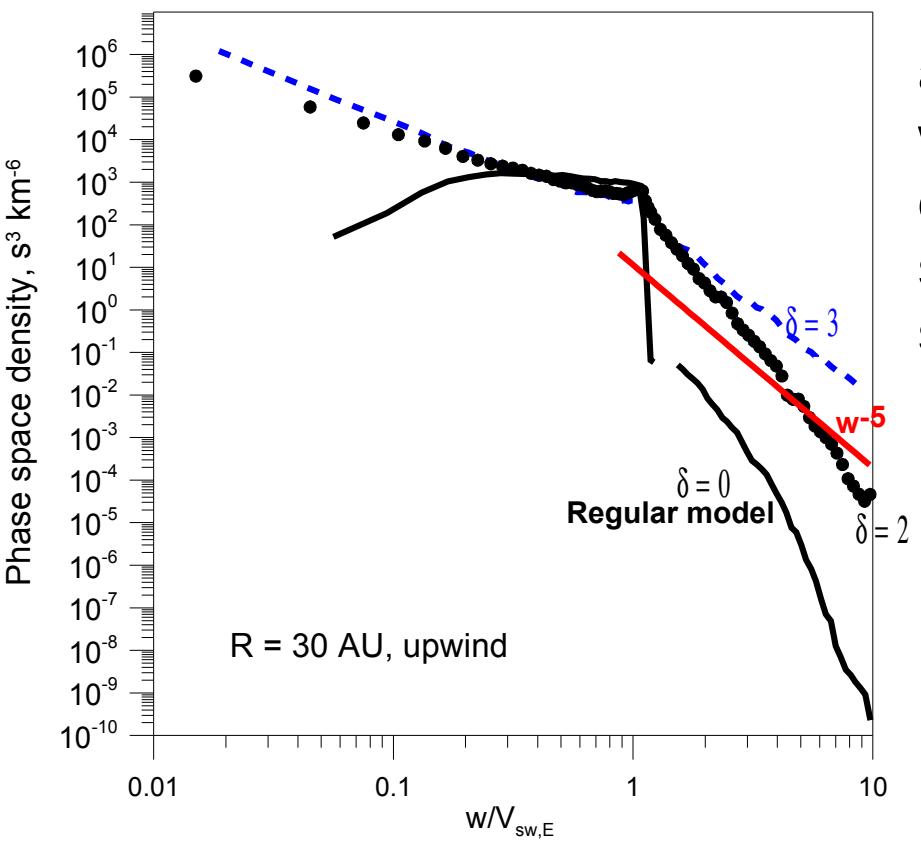


To test the stochastic acceleration by Alfvénic turbulence we solve the Fokker-Plank equation with diffusion coefficient from Chalov et al. (JGR, 2003). Dimensionless parameter β corresponds to the level of magnetic fluctuations.

Conclusions: 1) stochastic acceleration by Alfvénic turbulence in the supersonic solar wind does not form “ w^{-5} ”- tails of suprathermal pickup protons. In the supersonic solar wind it can not form the required tail even for unrealistically high values of β .

2) experimentally observed strong gradient in the phase space density at $w/V_{sw,E} \sim 1$ disappears in the models with effective stochastic acceleration.

Acceleration in the supersonic solar wind by density (velocity) fluctuations



To test Fisk & Gloeckler conception on acceleration in compressional turbulence we solve kinetic equation for pickup proton distribution function (with $D=0$) employing stochastic divergence of the supersonic solar wind flow.

$\text{div } \mathbf{u} = (\text{div } \mathbf{u})_{\text{reg}} (1 + \xi \delta)$, where $(\text{div } \mathbf{u})_{\text{reg}}$ is divergence of the solar wind in regular model, δ is the level of fluctuations;
 ξ random number between $[-1, 1]$.

$\delta = 2, 3$ are unrealistically high and chosen for test purposes.

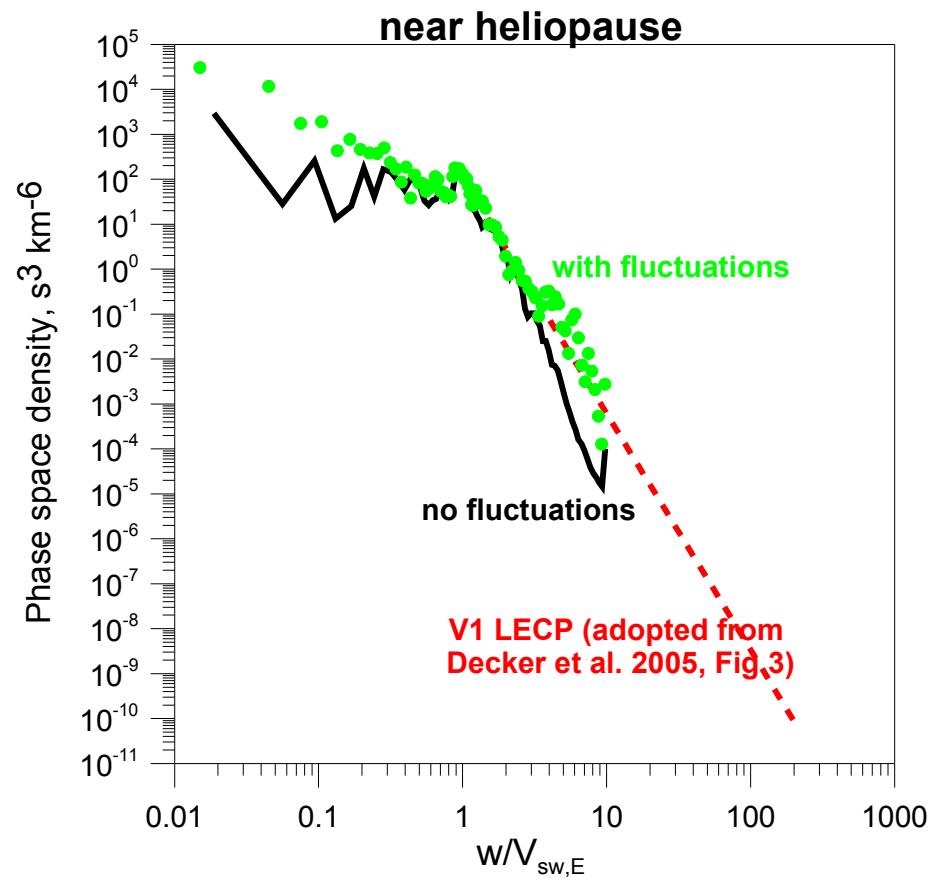
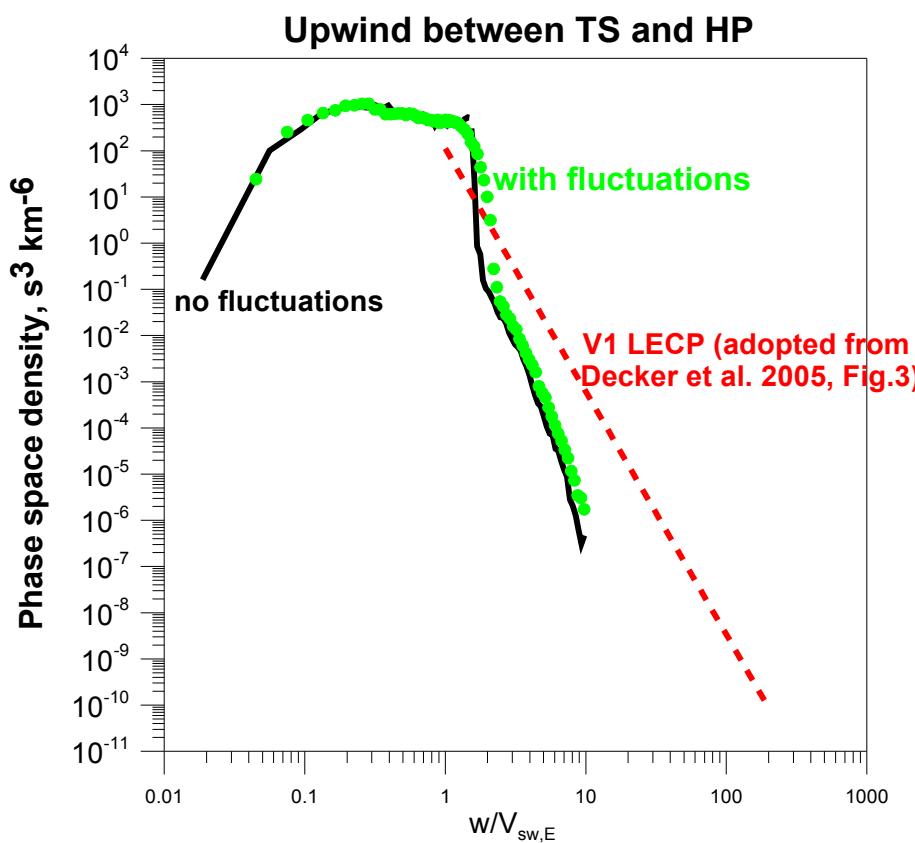
- Conclusions:** 1) stochastic acceleration in the compressional turbulence trends to form “ w^{-5} ” tails (blue curve, $\delta = 3$), but other processes not included in Fisk-Gloeckler consideration (i.e. sources of pickups) destroy the “ w^{-5} ”- shape;
2) In the supersonic solar wind it can not form the required tail even for unrealistically high values of δ .

Both mechanisms of pickup proton acceleration in the supersonic wind do not produce « w^{-5} »-tails even for marginally large parameters responsible for the acceleration mechanisms.

In the calculations where the acceleration is effective the models does not produce strong gradient in the phase space density at $w/V_{sw,E} \sim 1$ which is experimentally observed. Therefore, we conclude that acceleration mechanisms in the supersonic solar wind can not be major factors for the “ w^{-5} ”-tail formation.

Another possibility is the concept (Chalov&Fahr, 2003) that pickup proton tails in the supersonic solar wind are formed by ionization of Energetic Neutral Atoms (ENA) from the inner heliosheath.

Effects of regular compression and compressional turbulence in the inner heliosheath

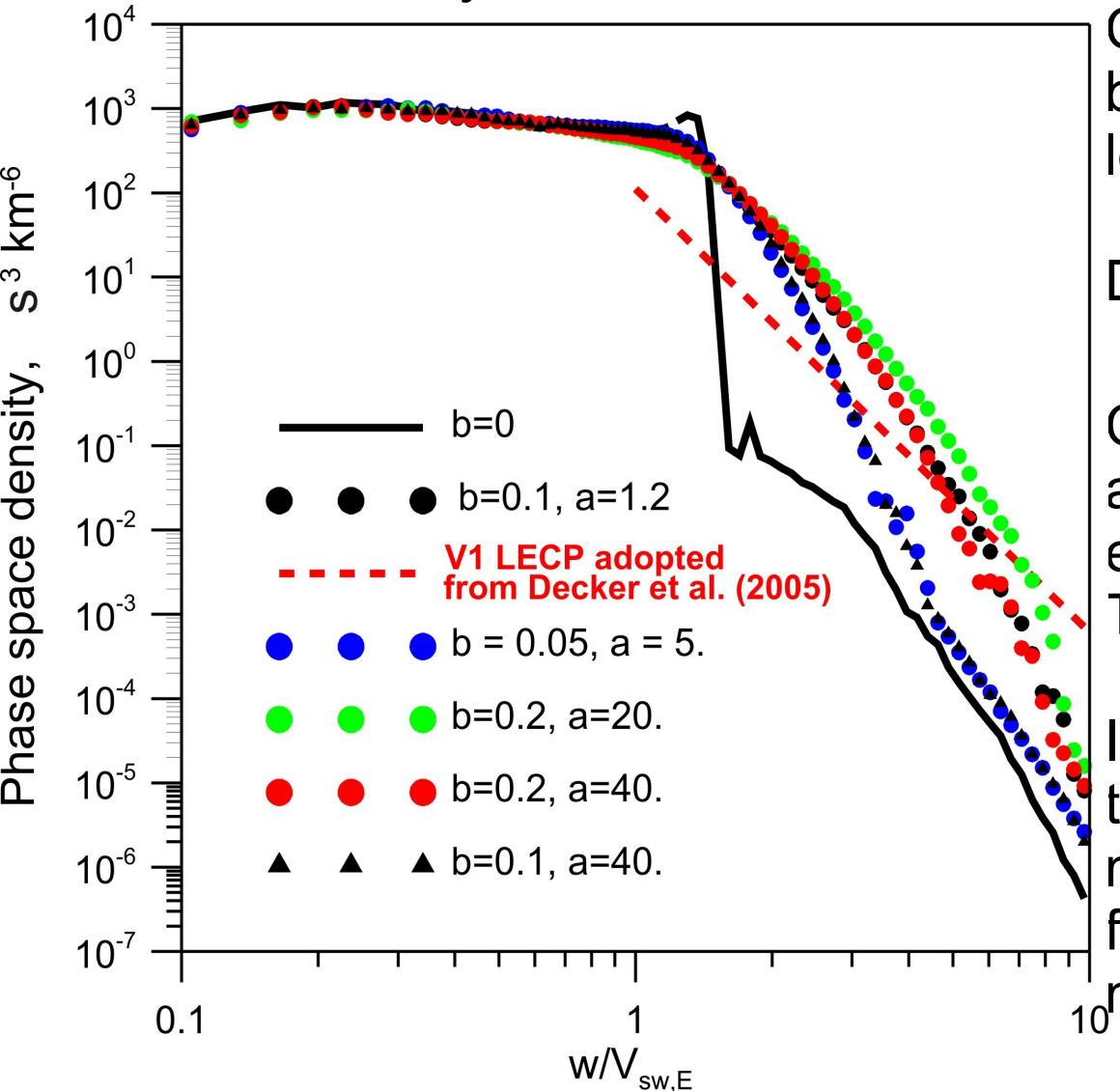


Solar wind velocity fluctuations are taken from Izmodenov, Malama, Ruderman (2005) model results; 15-days averages are used.

- Conclusions:**
- 1. Regular negative divergence of the solar wind speed inside the heliosheath results in formation of suprathermal tail with spectral index close to w^{-5} .**
 - 2. Effect of compressional turbulence on the spectra of pickup protons is not very important. Although qualitatively concept of Fisk and Gloeckler is confirmed (near the heliopause; see right figure).**

Effect of velocity-space diffusion in the inner heliosheath

In vicinity of the TS

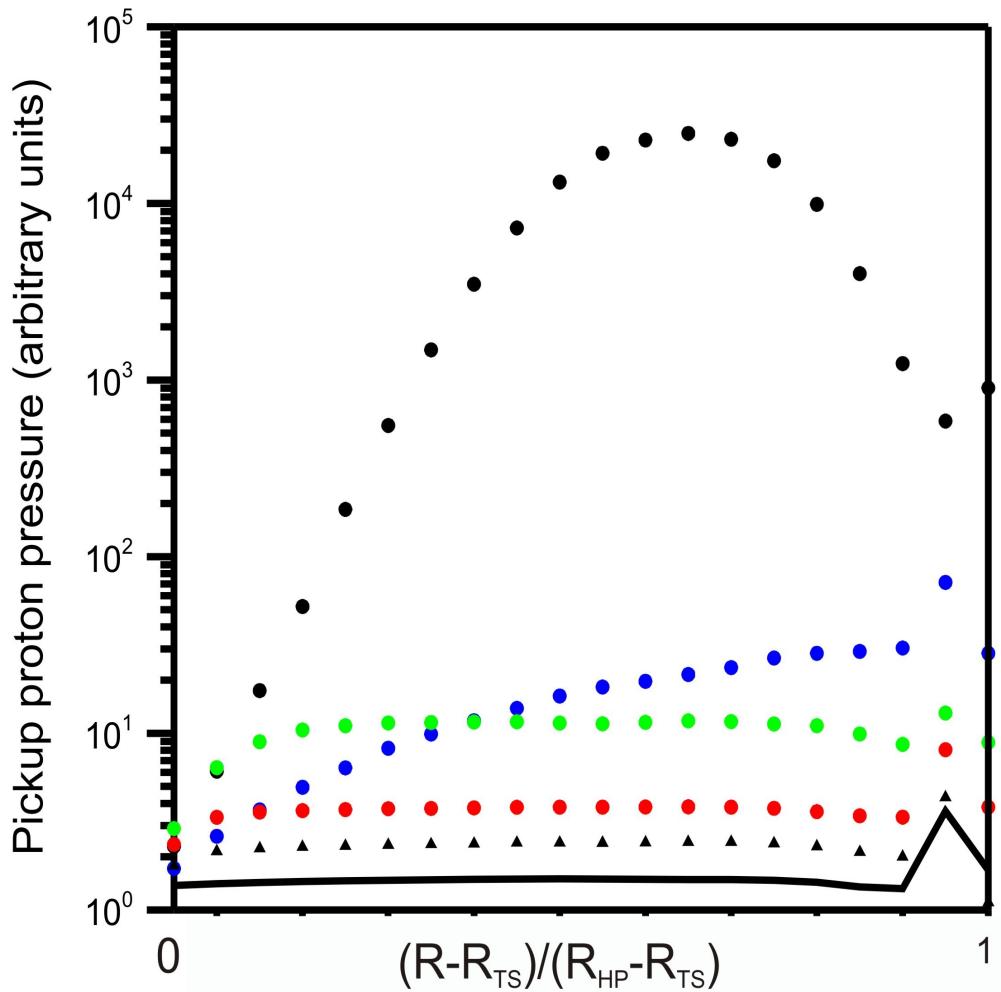


Diffusion coefficient is taken from Chalov et al. (JGR, 2003);
b is a parameter responsible for level of magnetic field fluctuations;
a is increment of spatial decay:
 $D=D_0 \exp[-a(R-R_{\text{TS}})/(R_{\text{HP}}-R_{\text{TS}})]$.

Chosen diffusion coefficient accelerates pickup protons very effectively immediately after the TS.

If one assumes $a=0$ (no decay of the level of fluctuations) then too much energy is transferred from fluctuations to pickup protons. (see next slide).

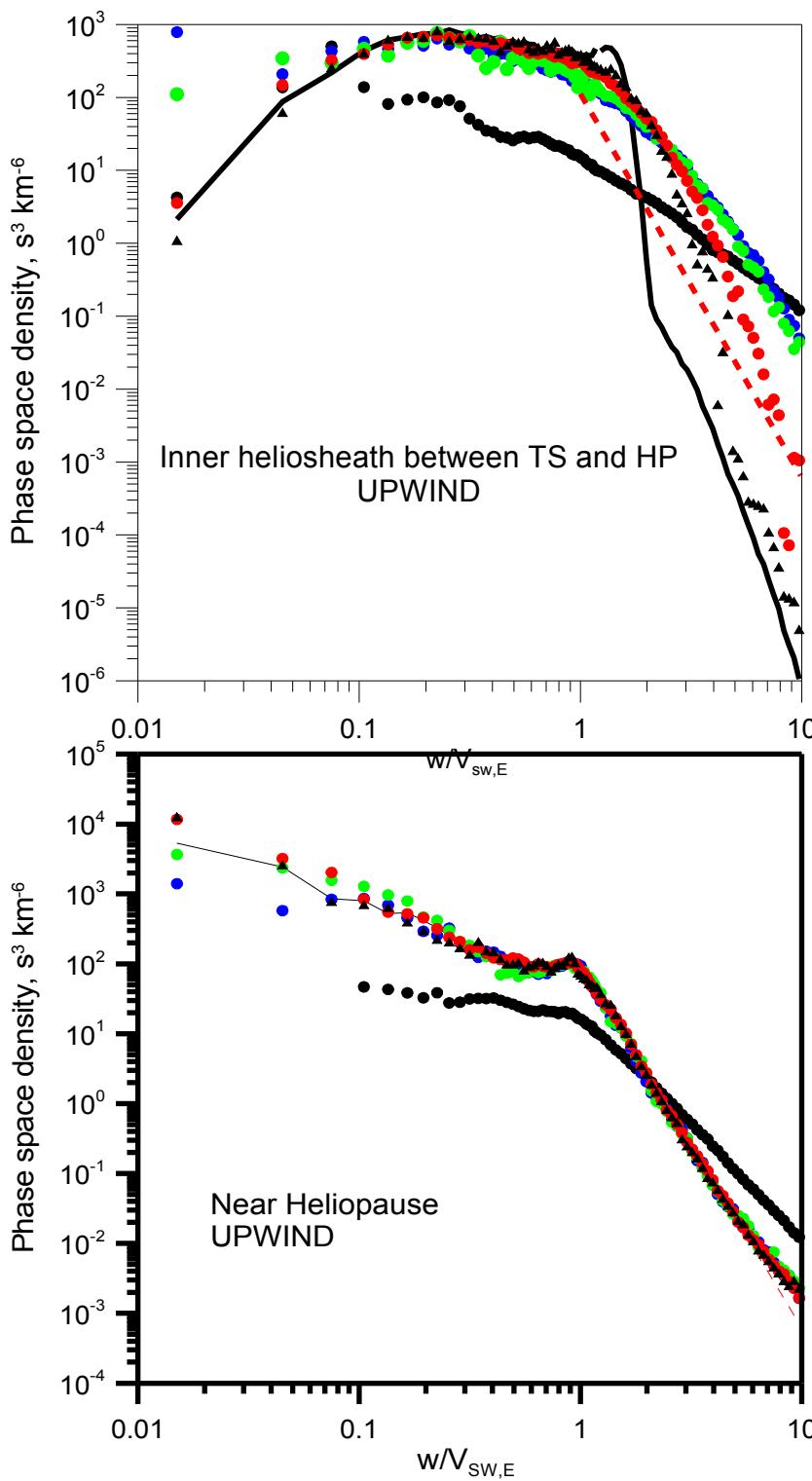
Illustration of energy deposition from magnetic field fluctuations to pickup proton thermal energy in the inner heliosheath for different parameters of calculations



The figure shows that due to chosen diffusion mechanism in the inner heliosheath too much energy is deposited into pickup proton component.

Only those calculations that have strong damping mechanism (i.e. red cycles and black triangles) have reasonable energy deposition.

Notations are the same as in previous fig.



Velocity-space diffusion forms suprathermal tails immediately after the TS. This might be important for formation of ENAs with $w/V_{sw,E} > 1$.

Due to introduced decay of the level of fluctuations, the role of velocity diffusion on pickup proton spectra becomes smaller when approaching the HP.

The regular compression becomes dominating.

In the case when increment of decay is small (black cycles) then the spectral index is essentially different from -5.

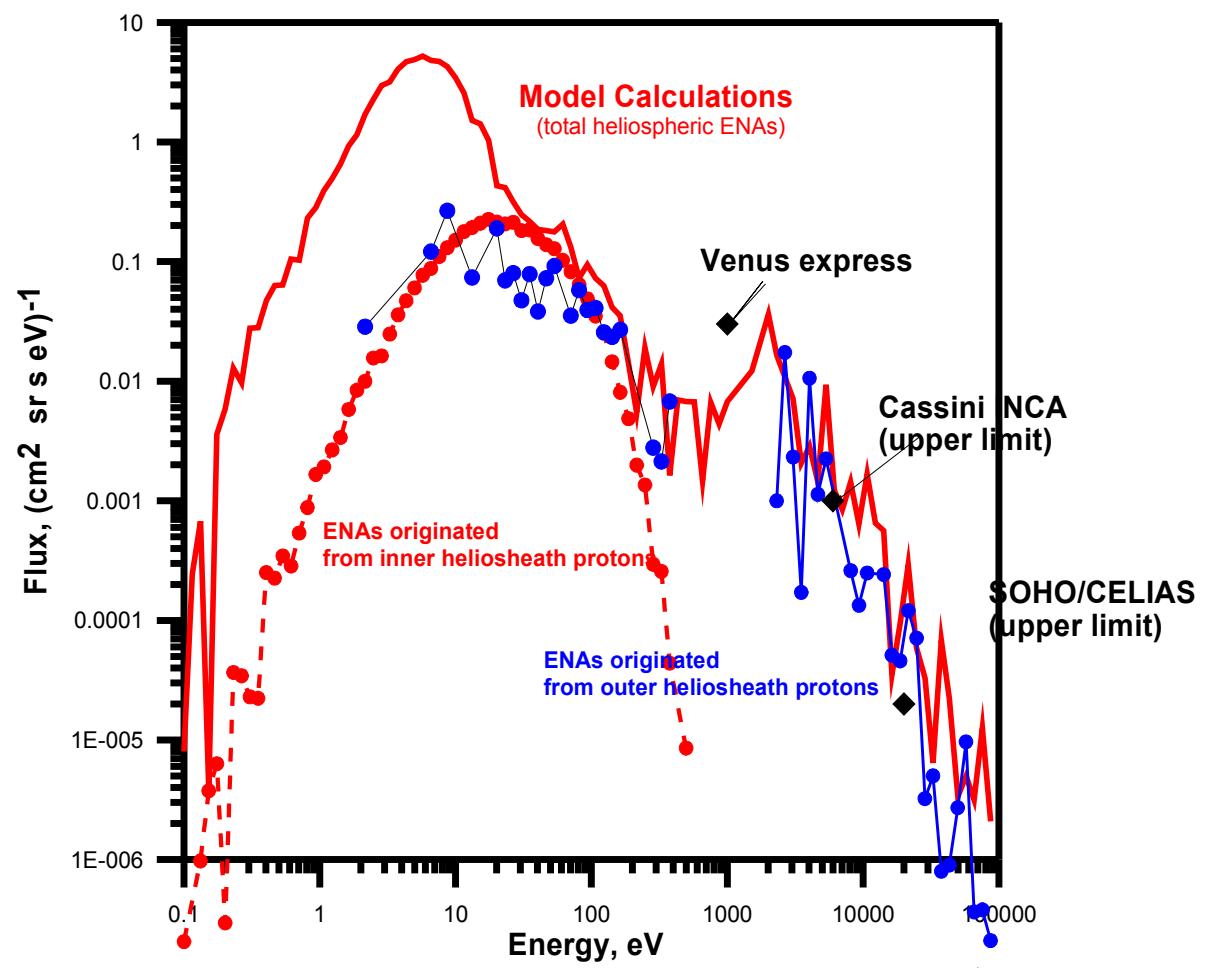
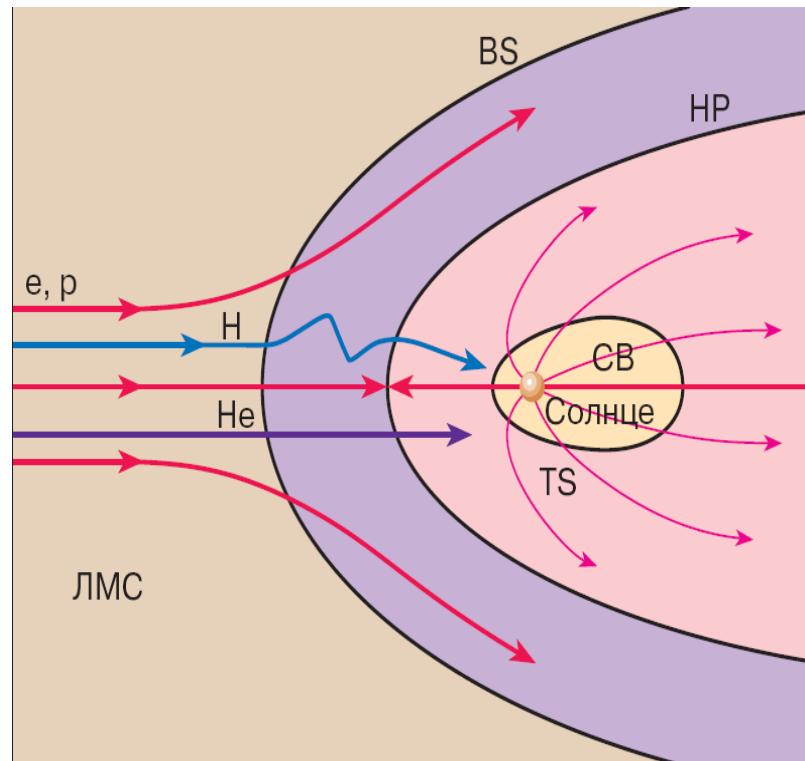
This means that to keep ' w^{-5} '-spectral index (as observed) the stochastic acceleration processes should be important in the vicinity of the TS only (not in the entire heliosheath).

CONCLUSIONS of Part 2 (preliminary)

Roles of different physical processes on formation of the « w^{-5} »- tails of suprathermal pickup protons have been examined.

- It was shown that stochastic acceleration by both Alfvénic and compressional turbulences are unlikely the sources of the tails. Although the latter process trends to « w^{-5} »- tail formation.
- Another « w^{-5} »- tail formation occurs in the vicinity of the heliopause due to regular compression (negative divergence of the solar wind speed).
- These tails can be transferred from the heliopause to inner heliosphere due to ENAs (that have large mean free path).
-
- Since the majority of heliospheric ENAs comes into the supersonic solar wind from the vicinity of the TS then one needs to seek for a mechanism of pickup proton acceleration in the vicinity of the shock and not extended too much inside the inner heliosheath. It has been shown (not self-consistently yet) that such a scenario is possible.

Гелиосферные ЭНА: что известно до IBEXа?



Потоки ЭНА (энергичных атомов) на 1 а.е.

Данные IBEX будут доступны в течение 2009 г.