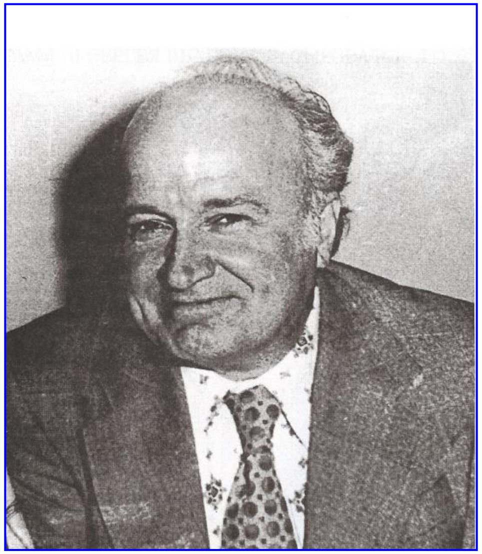
Сингулярные токовые структуры в космической плазме

Л.М. Зеленый (ИКИ РАН)

При участии: Х.В. Маловой (НИИЯФ МГУ), В.Ю. Попова (Физ. Ф-т МГУ), Е.Е. Григоренко (ИКИ РАН), В.И. Домрина (НИИЯФ МГУ)

Историческое фото: ИКИ-НИИЯФ



Работы С.И. Сыроватского по токовым слоям их устойчивости

Токовый слой как тепловой триггер солнечных вспышек:

- **Current-sheet parameters and a thermal trigger for solar flares**

  S. I. Syrovatskii — Sov. Astron. Lett., Vol. 2, No. 1, Jan.-Feb. 1976

- CURRENT SHEETS AS THE SOURCE OF HEATING FOR SOLAR ACTIVE REGIONS

  . SOMOV and S. I. SYROVATSKII

  ical Institute of the Academy of Sciences, Moscow, U.S.S.R.

  Solar Physics **55** (1977) 393–399.

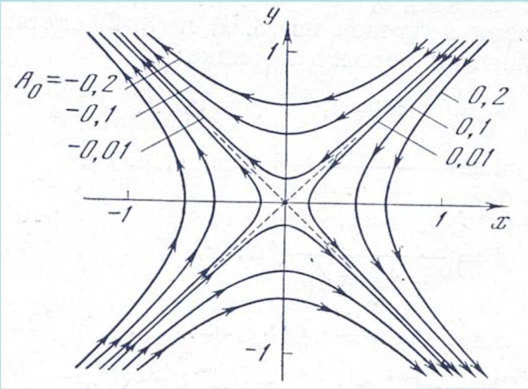
- **Effect of external plasma on the decay of a neutral current sheet**

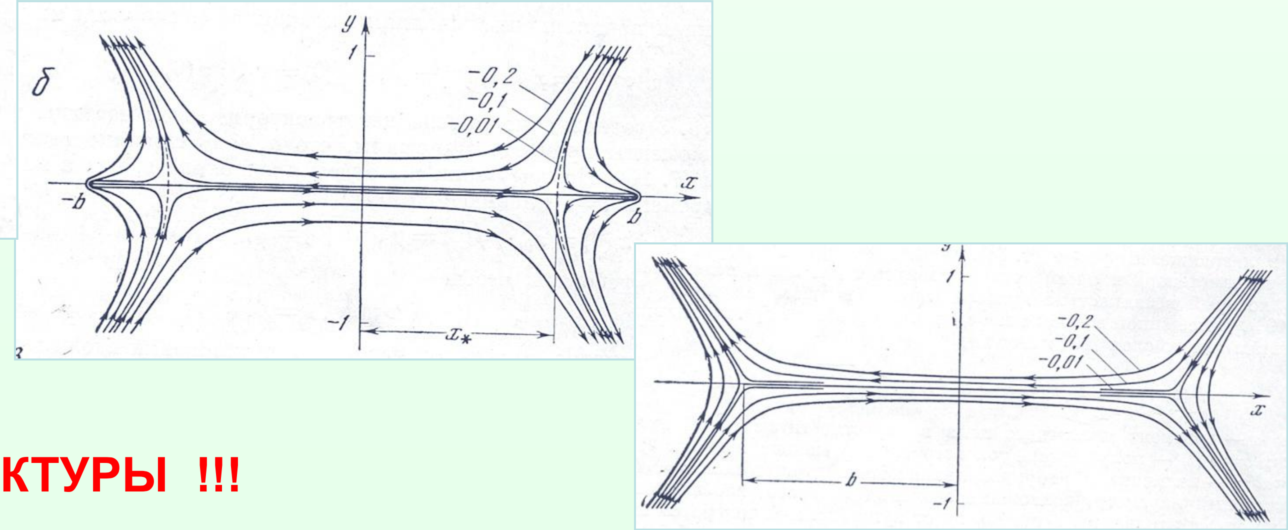
  Pis'ma Zh. Eksp. Teor. Fiz. **26**, No. 11, 729–732

  S. V. Bulakov, N. V. Sasorov, and S. I. Syrovatskiĭ

- DEVELOPMENT OF A CURRENT LAYER WHEN PLASMA MOVES IN A MAGNETIC FIELD WITH A NEUTRAL LINE

  S.I. Syrovatskii, A.G. Frank, and A.Z. Khodzhaev
  P.N. Lebedev Physics Institute, USSR Academy of Sciences
  Submitted 21 December 1971
  ZhETF Pis. Red. 15, No. 3, 138 - 142 (5 February 1972)



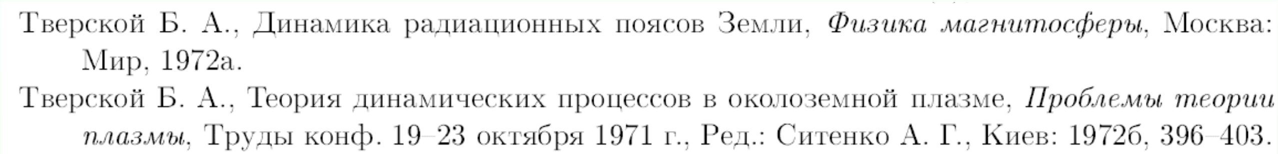


ТС В МГД

СИНГУЛЯРНЫЕ СТРУКТУРЫ !!!

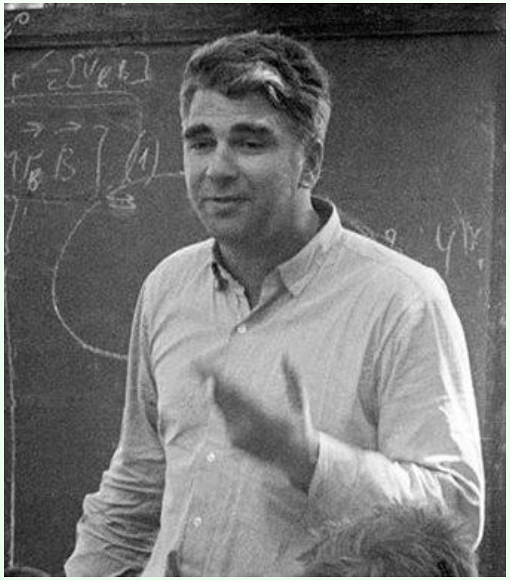
Идеи Б.А. Тверского и В.П. Шабанского легли в основу исследований НИИЯФ/ИКИ плазменных слоев в космосе

Б.А. Тверской предложил модель изотропного токового слоя (Тверской, 1972). В ней впервые использовал адиабатические инварианты движения частиц в модели ТС.

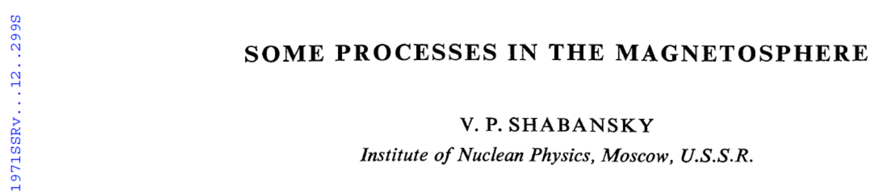


Тверской Б. А., Динамика радиационных поясов Земли, *Физика магнитосферы*, Москва: Мир, 1972а.

Тверской Б. А., Теория динамических процессов в околоземной плазме, *Проблемы теории плазмы*, Труды конф. 19–23 октября 1971 г., Ред.: Ситенко А. Г., Киев: 1972б, 396–403.



В.П. Шабанский – идеи параболоидной модели магнитосферы (Shabansky, SSR, 1971; в кн. Явл. околозем. косм. простр., 1972); разрезного кольцевого тока; нарушения адиабатических инвариантов движения частиц; впервые описал вложенность токового слоя.



1971SSRv...12..299S

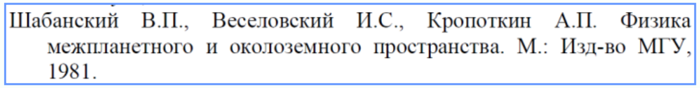
SOME PROCESSES IN THE MAGNETOSPHERE

V. P. SHABANSKY

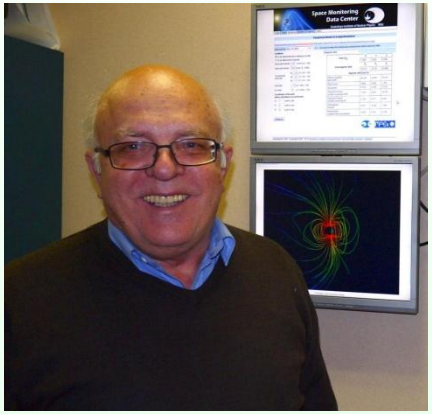
Institute of Nuclean Physics, Moscow, U.S.S.R.

Развитие моделей магнитосферных токовых систем и токовых слоев разных конфигураций

А.П. Кропоткин: теория формирования ВКТС – вынужденного кинетического токового слоя (Kropotkin&Domrin, 1995-2007)

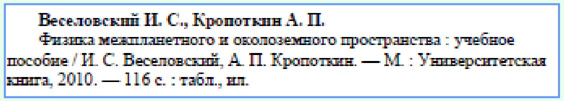


Шабанский В.П., Веселовский И.С., Кропоткин А.П. Физика межпланетного и околоземного пространства. М.: Изд-во МГУ, 1981.

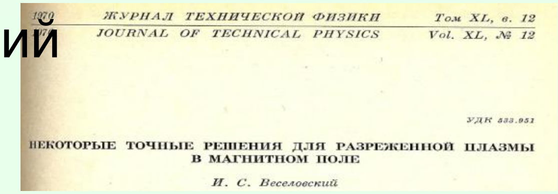


И.И Алексеев (работы с 1993г. по настоящее время): развитие параболоидной модели магнитосферы Земли; последующее обобщение ее на магнитосферы других планет солнечной системы, гелиосферу, экзопланеты.

И.С. Веселовский: развитие моделей гелиосферного токового слоя в солнечном ветре, изучение плазменных равновесий



Веселовский И. С., Кропоткин А. П.
Физика межпланетного и околоземного пространства : учебное пособие / И. С. Веселовский, А. П. Кропоткин. — М. : Университетская книга, 2010. — 116 с. : табл., ил.



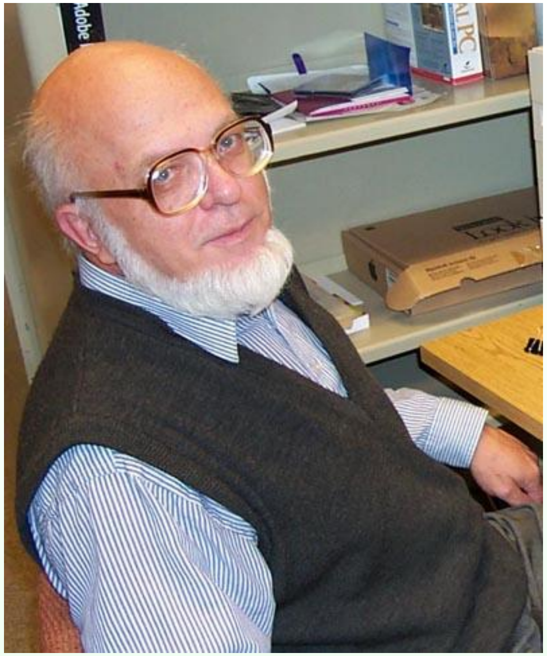
1970 *ЖУРНАЛ ТЕХНИЧЕСКОЙ ФИЗИКИ* *Том XL, в. 12*
1970 *JOURNAL OF TECHNICAL PHYSICS* *Vol. XL, № 12*

УДК 533.951

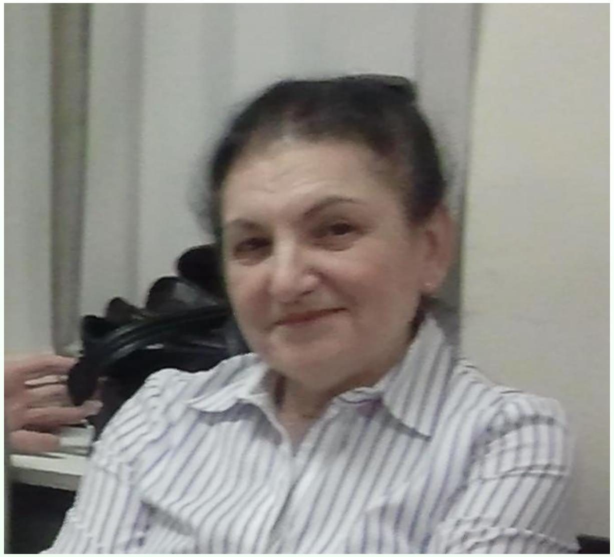
НЕКОТОРЫЕ ТОЧНЫЕ РЕШЕНИЯ ДЛЯ РАЗРЕЖЕННОЙ ПЛАЗМЫ В МАГНИТНОМ ПОЛЕ

И. С. Веселовский

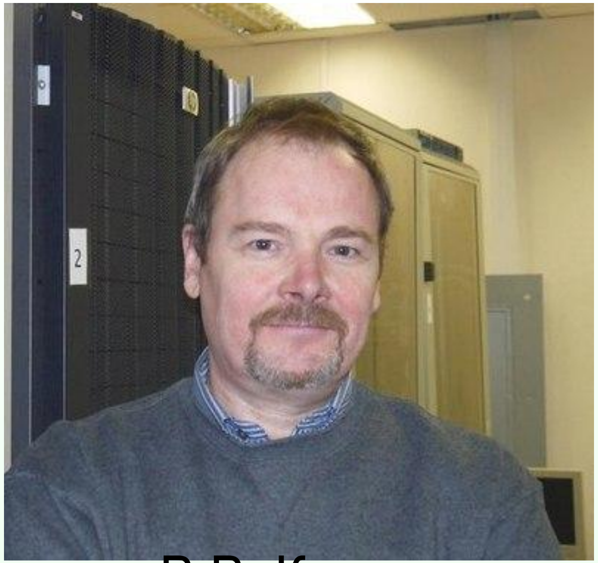
Группа И.И. Алексеева – исследование планетных магнитосфер, развитие параболоидной модели магнитосферы



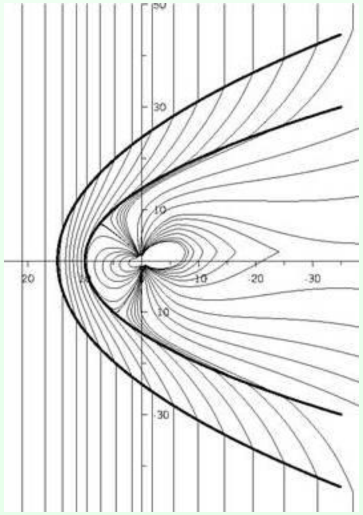
И.И. Алексеев



Е.С. Беленькая



В.В. Калегаев



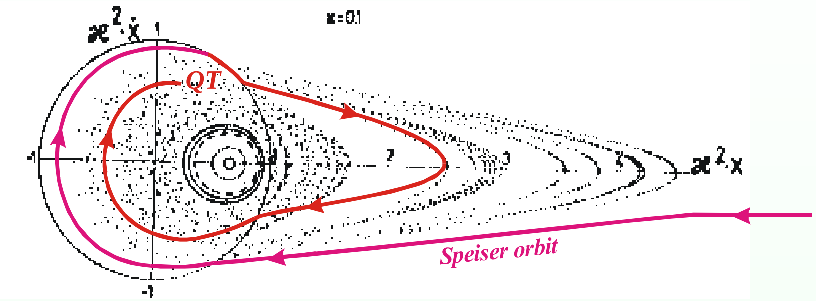
Х.В. Малова и
М.С.Блохина

Квазиадиабатическое описание движения «незамагниченных»частиц

Iz

(Buechner and Zelenyi, JGR, 1989)

$$I_z = \frac{1}{2\pi}\oint m v_z dz$$



СЛАБО РЕГУЛЯРНОЕ
И ТОЛЬКО ИНОГДА ХАОТИЧЕСКОЕ ДВИЖЕНИЕ

Скачки квазиадиабатического инварианта ΔIz

$$\Delta \bar{I} \cong \mu \frac{3}{2} \kappa \sqrt{1-(\bar{I})^{4/3}} \ln 2\left|\cos\theta_{sep}\right|$$

Neistadt, 1986; Timofeev, 1978
Cary, Escande, Tennyson, 1986

$$\left\langle \Delta \bar{I} \right\rangle_{\theta sep} \equiv \frac{1}{2\pi}\int_0^{2\pi} \Delta \bar{I}\, d\theta = 0$$

Диффузия между спейсеровской и квазизахваченной областями

$$\left\langle (\Delta \bar{I})^2 \right\rangle_{\theta sep} \equiv \frac{1}{2\pi}\int_0^{2\pi} (\Delta \bar{I})^2\, d\theta = \frac{3\pi}{16}\kappa^2\left[1-(\bar{I})^{4/3}\right]$$

$$D_{I'I'} = \frac{\left\langle (\Delta \bar{I})^2 \right\rangle}{T_{QT}} = \frac{3\pi^2}{16 T_{QT}}\kappa^2\left[1-(\bar{I})^{4/3}\right]$$

Развитие моделей тонких токовых слоев (ТТС) в рамках квазиадиабатического приближения в космической плазме

М.И. Ситнов

Kropotkin, Malova, Sitnov, JGR, 1997 –
модель ТТС в пределе сильной анизотропии;

Sitnov,Zelenyi,Malova JGR, 2000 –
модель ТТС для произвольной анизотропии

Zelenyi et al., NPG, 2000
– модель ТТС с учетом влияния электрического поля и оценкой масштабов

Domrin et al., 2016-2021 –
исследование структуры вложенных ТТС
В рамках динамической и стационарной моделей

В.И. Домрин и Х.В. Малова

Команда ИКИ- в содружестве с МГУ- ИЗМИРАН - ПГИ: развитие теории ТТС в космосе и сопоставление с экспериментальными данными

Развитие теории ТТС в хвосте магнитосферы Земли; в применении к магнитосферам планет; в солнечном ветре; в м/сферах экзопланет

В.Ю. Попов

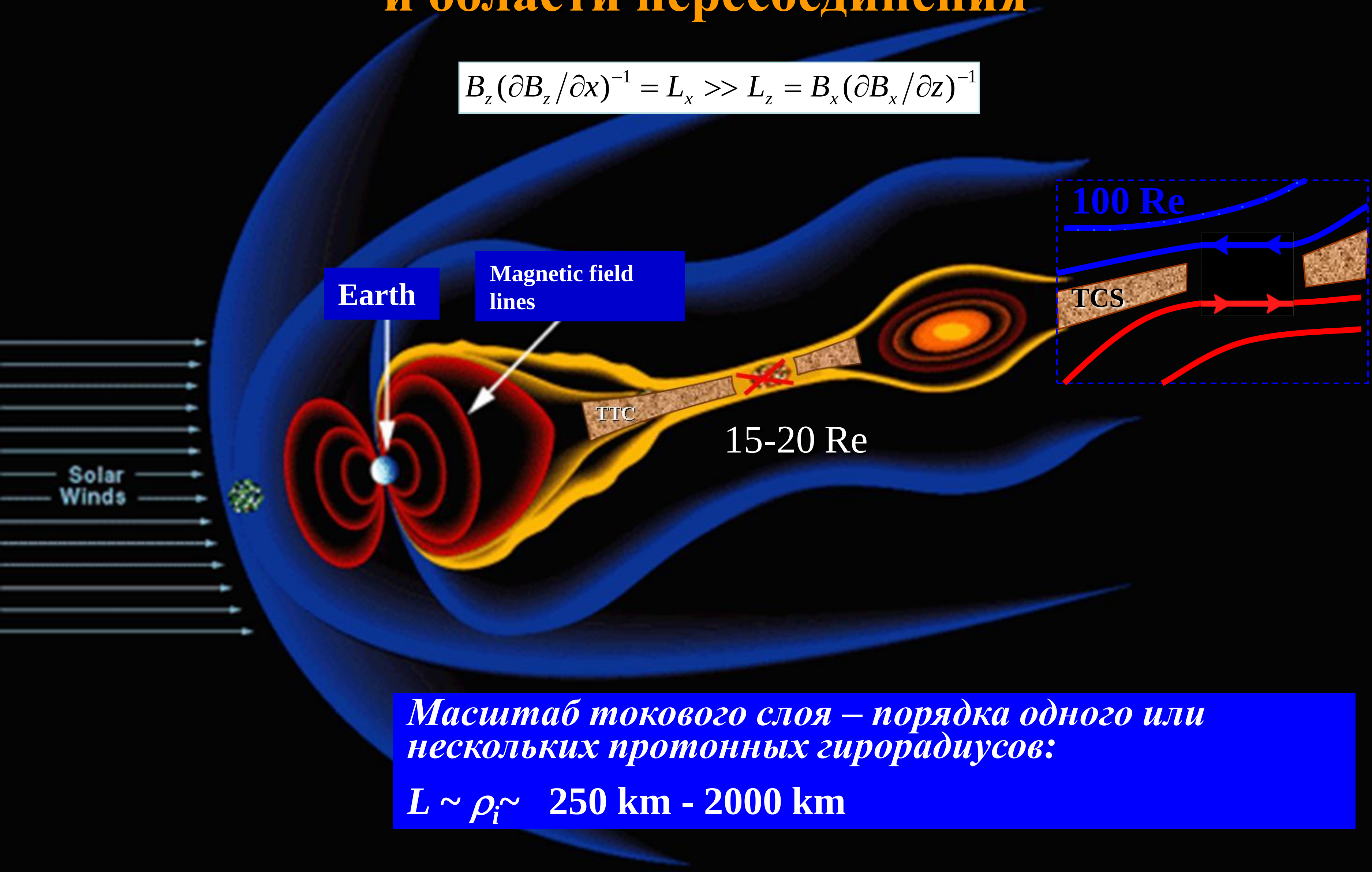
Е.Е. Григоренко

Р.А.Кислов

О.В. Хабарова и
О.В. Мингалев

Токовый слой в хвосте магнитосферы Земли и области пересоединения

$$B_z(\partial B_z/\partial x)^{-1} = L_x >> L_z = B_x(\partial B_x/\partial z)^{-1}$$

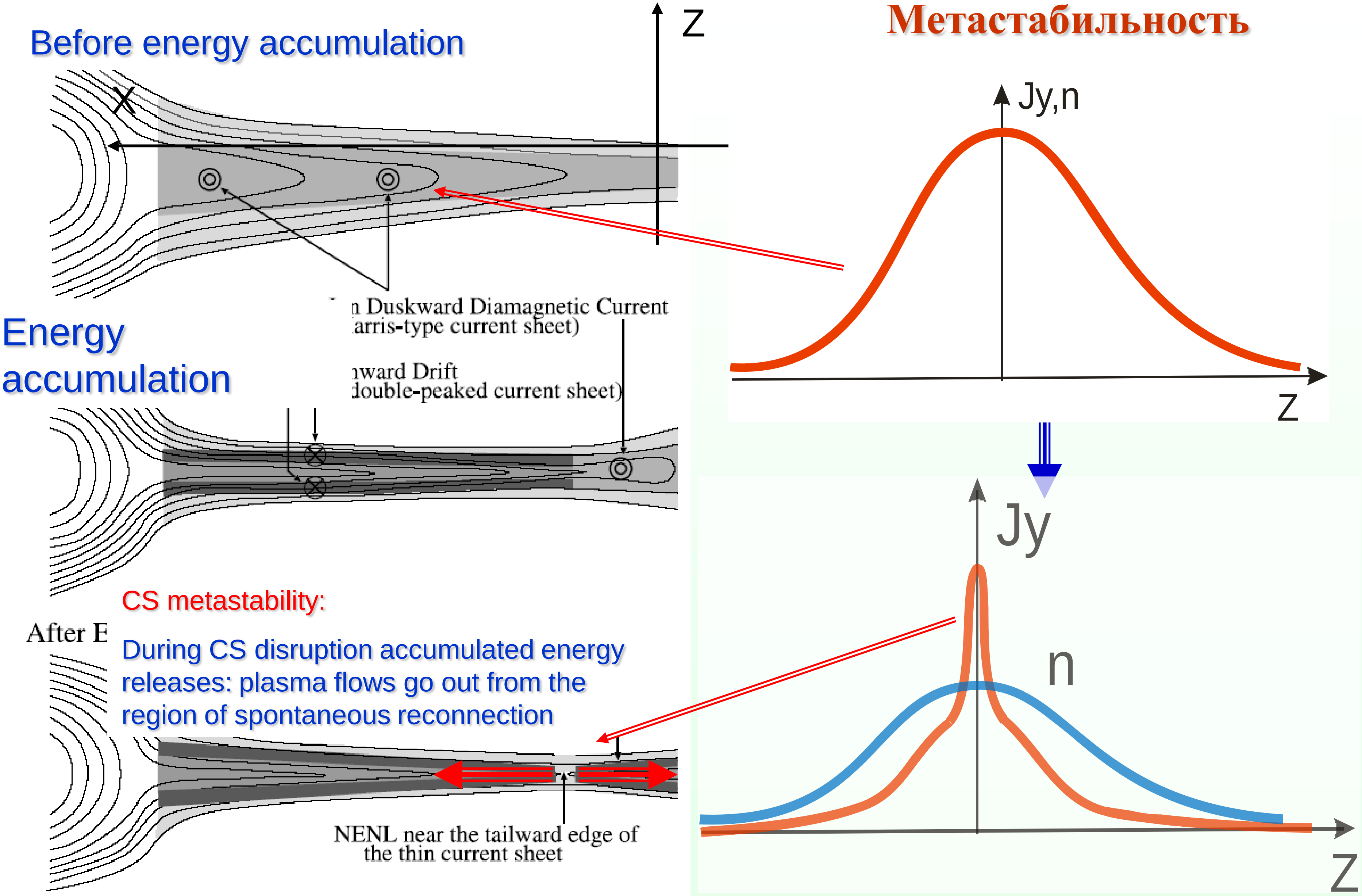


Масштаб токового слоя – порядка одного или нескольких протонных гирорадиусов:

$L \sim \rho_i \sim$ **250 km - 2000 km**

Эволюция ТС до начала высвобождения энергии.

Метастабильность



Before energy accumulation

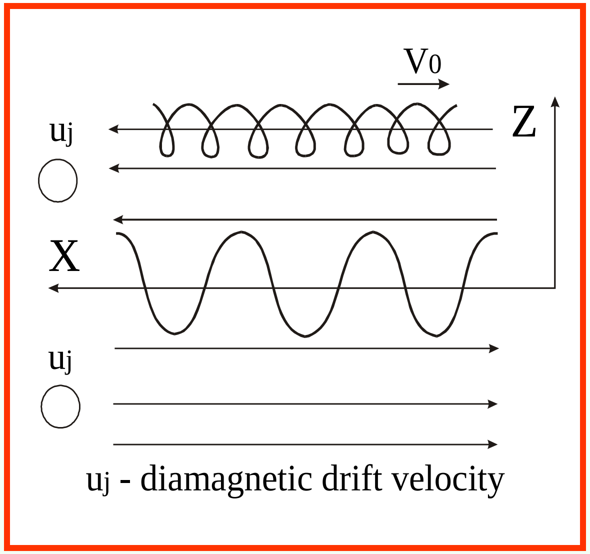
Energy accumulation

CS metastability:

During CS disruption accumulated energy releases: plasma flows go out from the region of spontaneous reconnection

Figure 18. Schematic picture of the current sheet evolution around the onset.

Равновесие Харриса



$$f_{0j}=\frac{n_0}{ch^2(z/L)}\exp\left(\frac{m_j[(\mathrm{v}_x-V_0)^2+(\mathrm{v}_y-u_j)^2+\mathrm{v}_z^2}{2T_j}\right)$$

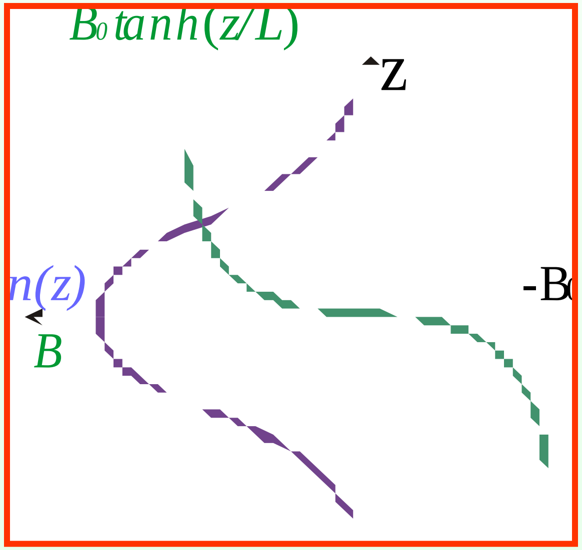
$$\frac{u_e}{T_e}+\frac{u_i}{T_i}=0,\qquad L=\frac{c}{\omega_{pi}}\frac{\mathrm{v}_{Ti}}{u_i}\sqrt{\frac{T_i}{T_e+T_i}}$$

PROFILES of current and density <u>COINCIDE</u>

$$B_x=B_0\tanh\left(\frac{z}{L}\right)$$

$$\frac{B_0^2}{8\pi}=n_0\left(T_{e\perp}+T_{i\perp}\right)$$

$$n(z)=\frac{n_0}{ch^2\left(z/L\right)}$$



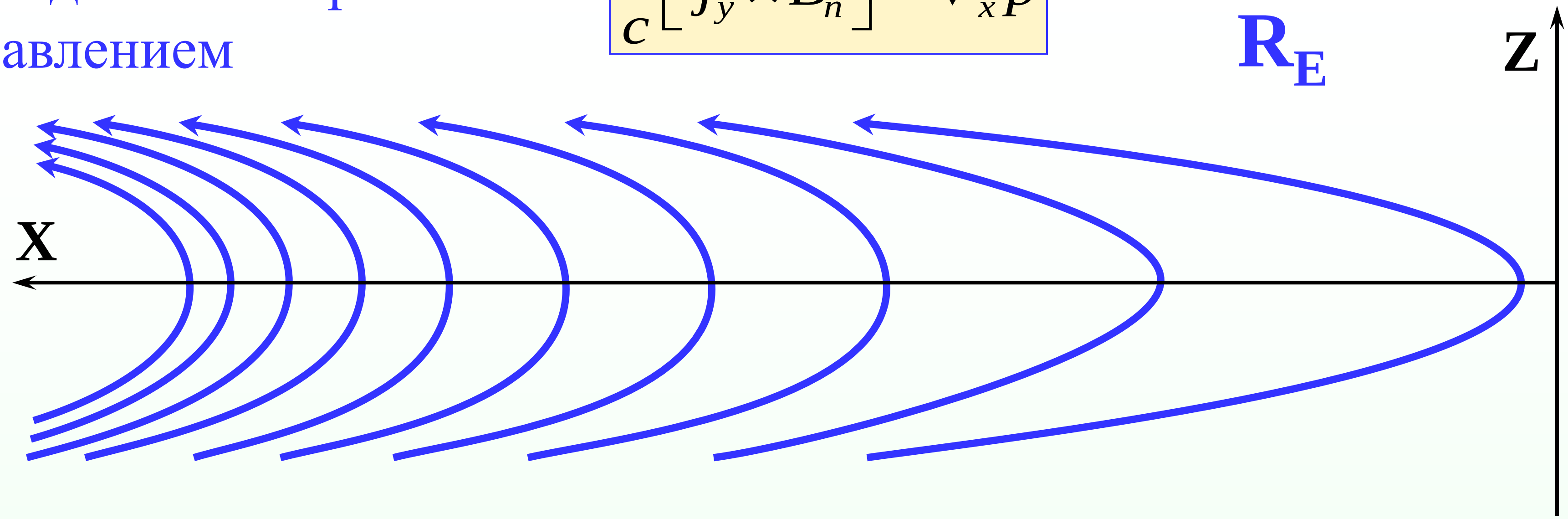
$$J_y(z)=\sum_j e_j n_j u_j=\frac{c}{B^2}\left|\vec{B}\times\nabla p_{\perp j}\right|=\frac{J_0}{ch^2\left(z/L\right)}$$

diamagnetic current

Модели с изотропным давлением

$$\frac{1}{c}\left[j_y \times B_n \right] = \nabla_x p$$

$L_x < 20\text{-}30\ R_E$

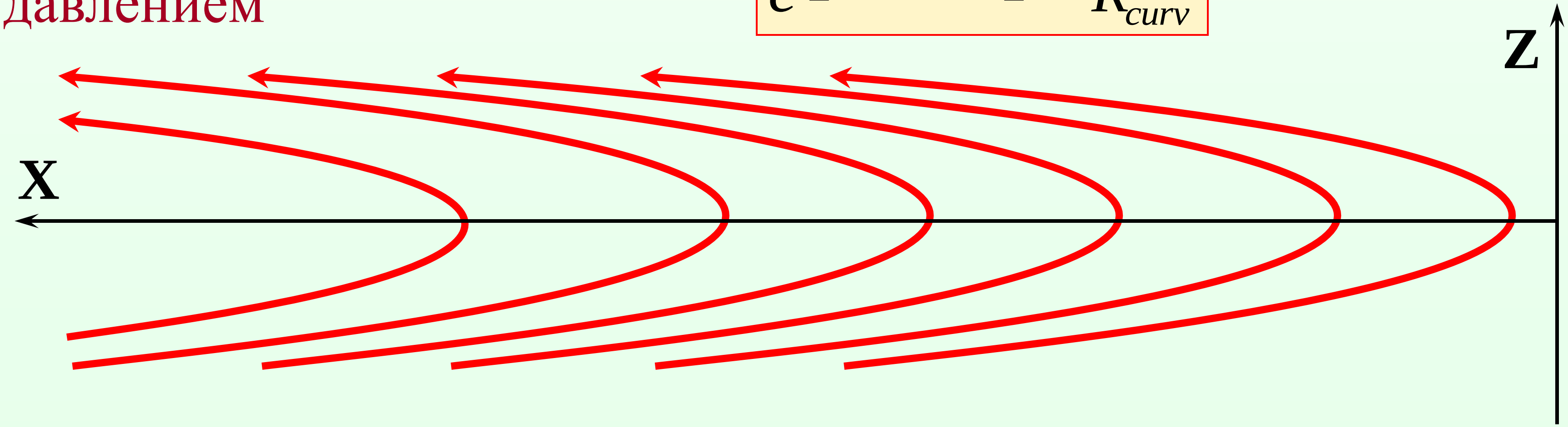


ТТС - Новый тип плазменного равновесия

Модели с анизотропным давлением

$$\frac{1}{c}\left[j_y \times B_n \right] = \frac{\rho v_P^2}{R_{curv}}$$

$L_x \to \infty$



Три типа токовых слоев, по данным спутников Cluster

(Runov et al., Annales Geophysicae, 24, 247–262, 2006)

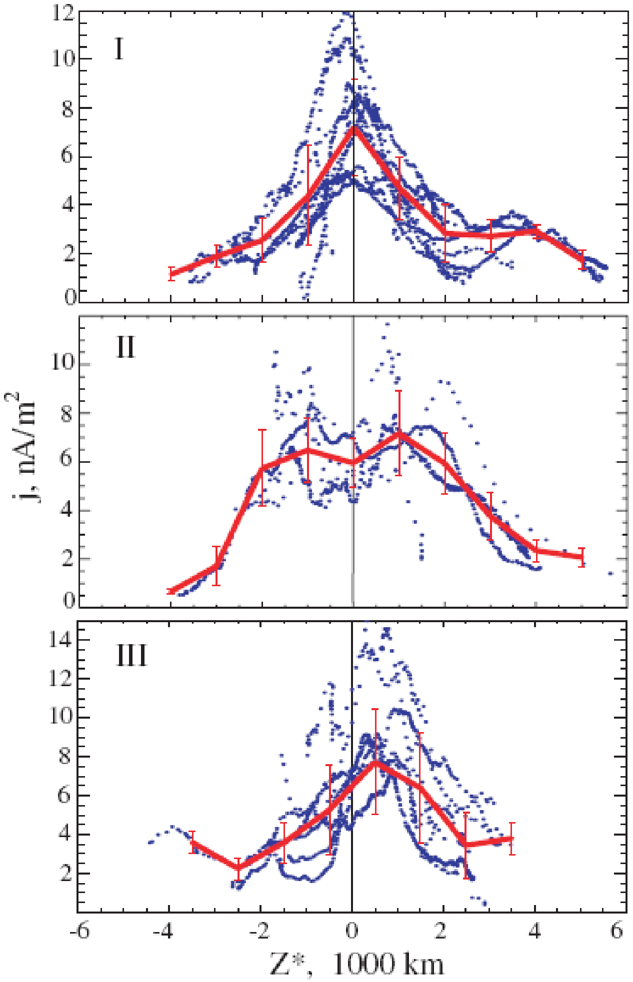
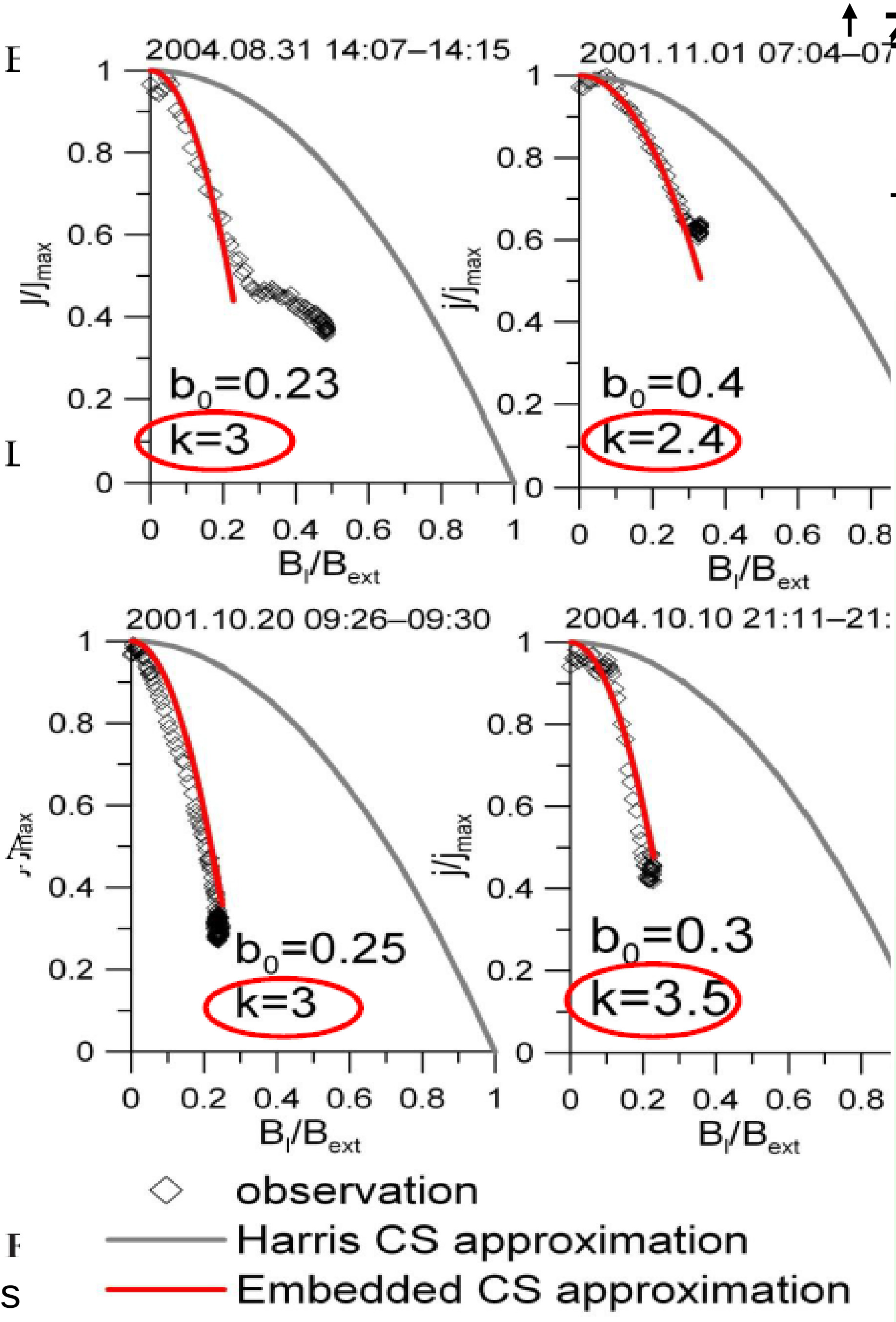


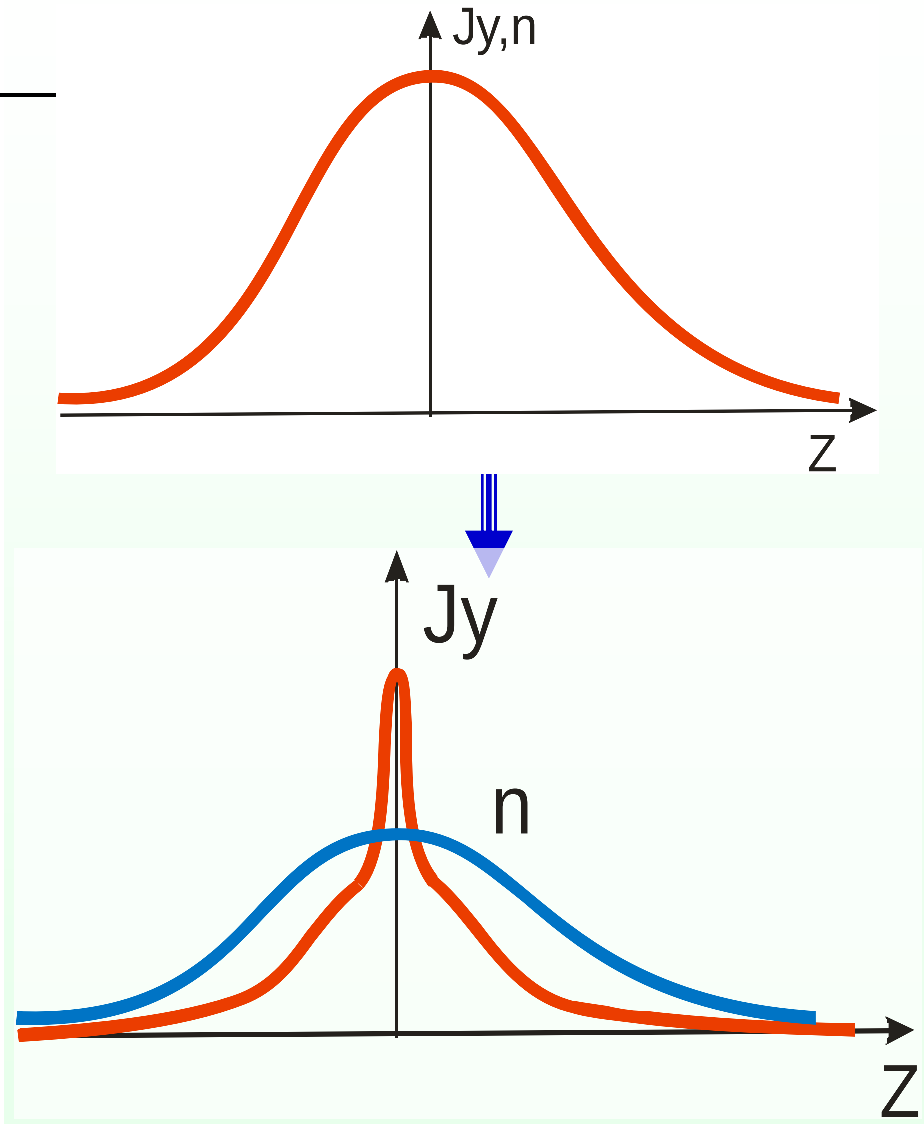
Fig. 4. Averaged vertical profiles of the current density for center peaked (class I), bifurcated (class II), and asymmetric (class III) current sheets. The Z* is calculated using Eq. (3).

Свойства ТТС:

- **Вложенность**
- **Анизотропия функции распределения ионов, быстрые плазменные потоки вдоль силовых линий**
- **Малая толщина – порядка нескольких протонных гирорадиусов**
- **1-2- пика на профиле плотности тока, асимметрия**
- **Вертикальные флаппирующие колебания (ΔB~several tens of nT, time period T~10 sec – several minutes)**

Эволюция ТС до начала взрывной фазы





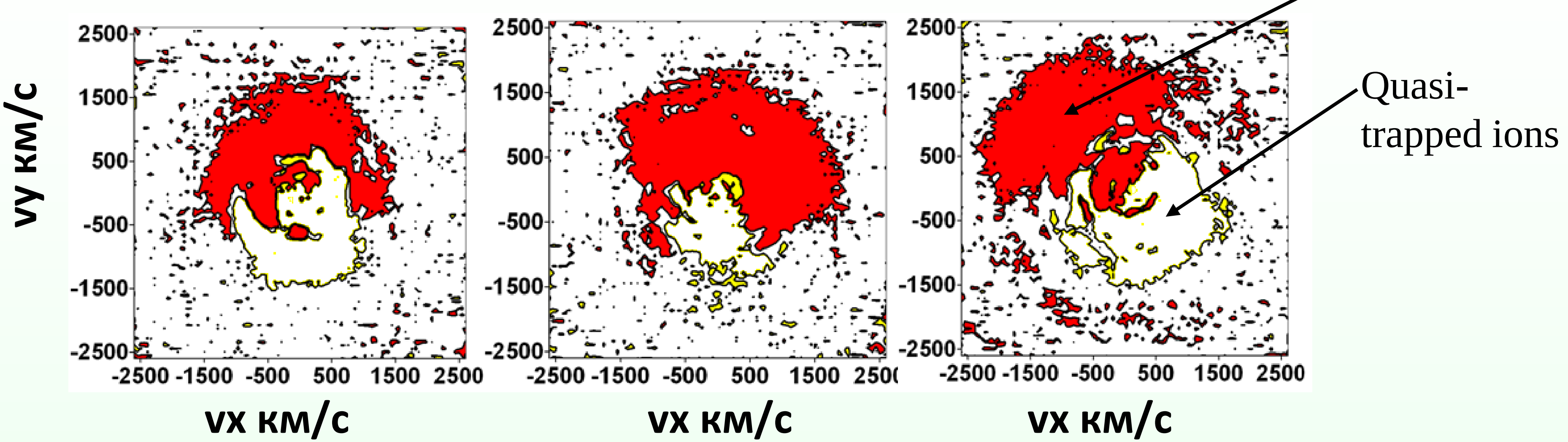
As

Зеленый и др., УФН, 2010

Функция распределения ионов негиротропна

$$\hat{\mathbf{P}} \neq P_{\perp}\hat{\mathbf{I}}_2 + \frac{(P_{||} - P_{\perp})\,\mathbf{BB}}{B^2}$$

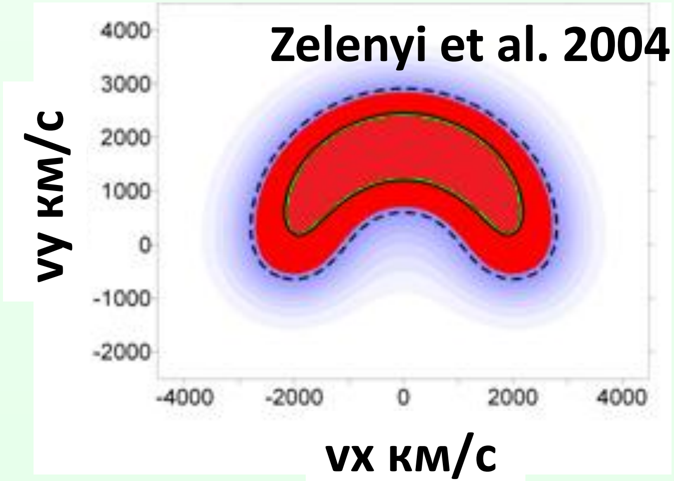
3 cases of thin current sheets



Speiser ions

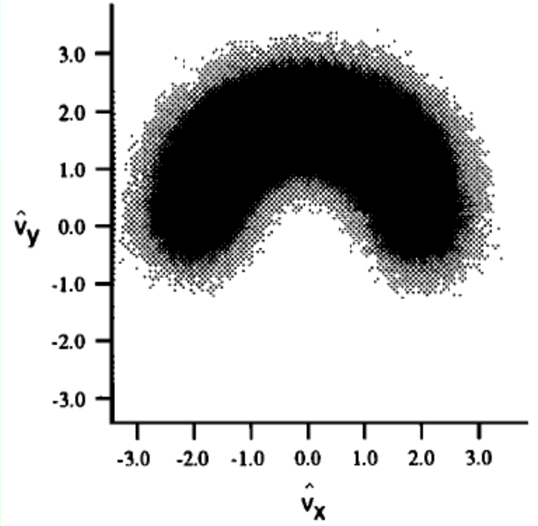
Quasi-trapped ions

Results of analytical model

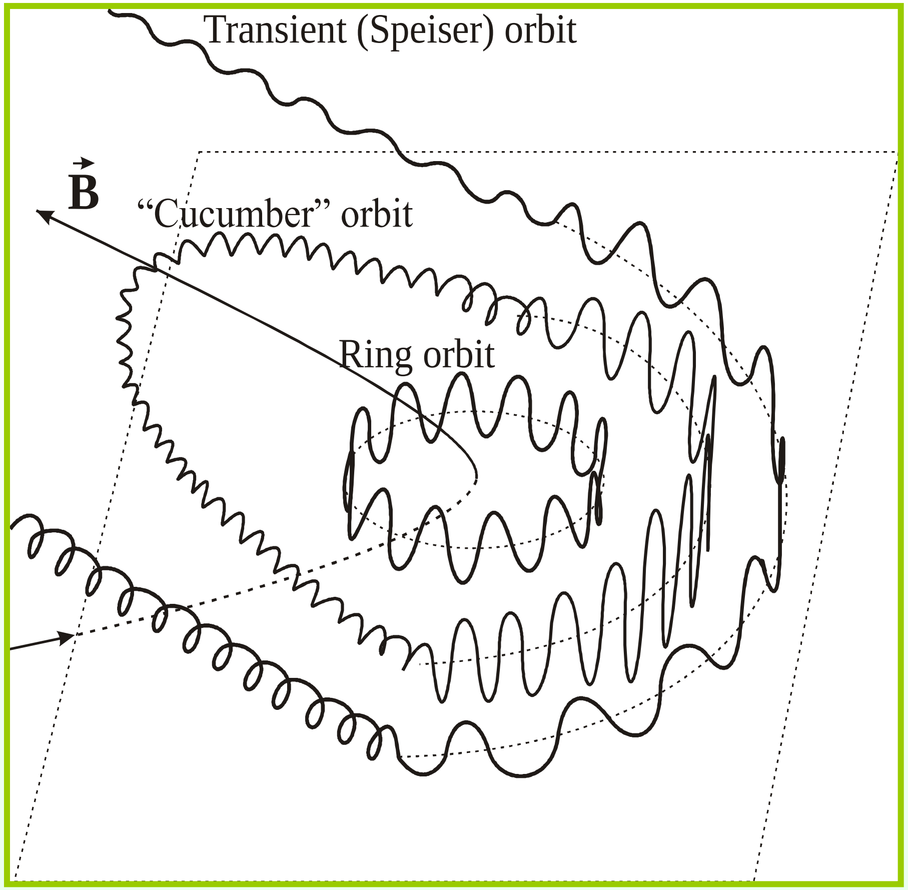


Particle-in cell model

Burkhart et al. 1992



Квазиадиабатическое движение протонов в хвосте магнитосферы Земли



$$W_0 = \frac{mv_0^2}{2}$$

$$P_y = mv_y - \frac{e}{c} A_y(x,z)$$

$$\boxed{I_z = \oint mv_z dz \approx const}$$

Quasiadiabatic approximation:

$$\boxed{\Delta I \cong \mathrm{m}\frac{3}{2}\kappa\sqrt{1-(\bar{I})^{4/3}}\,\ln 2\left|\cos\theta_{sep}\right| = I}$$

Neistadt, 1986; Timofeev, 1978
Cary, Escande, Tennyson, 1986

$$\kappa = \sqrt{\frac{R_{c\min}}{\rho_{\max}}} = 1 \qquad R_{\min} = \frac{b_n}{db/dz}\Big|_{z=0}$$

Уравнения Власова-Максвелла для квазиадиабатических ионов

$$df/dt = 0$$

$$\frac{dB}{dz} = \frac{4\pi}{c}\left\{\int_{V^3} v_y f_{trans}(\vec{v})d^3v + \int_{V^3} v_y f_{trap}(\vec{v})d^3v + j_e\right\}$$

$$B\big|_{z=L} = B_0,\ \varphi\big|_{z=L} = 0$$

$$f_{transient}(\vec{v}) = \frac{n_{0j}}{\left(\sqrt{\pi}v_{Tj}\right)^3}\exp\left\{-\frac{\left(v_{II} - v_{Dj}\right)^2}{v_{Tj}^2} - \frac{v_\perp^2}{v_{Tj}^2}\right\},\ v_\mathrm{P} > 0$$

$$f_{trap}(\vec{v}) = \frac{n_{0j}}{\left(\sqrt{\pi}v_{Tj}\right)^3}\exp\left\{-\frac{v_{Dj}^2 + v_\perp^2}{v_{Tj}^2}\right\},\ v_\mathrm{P} = 0$$

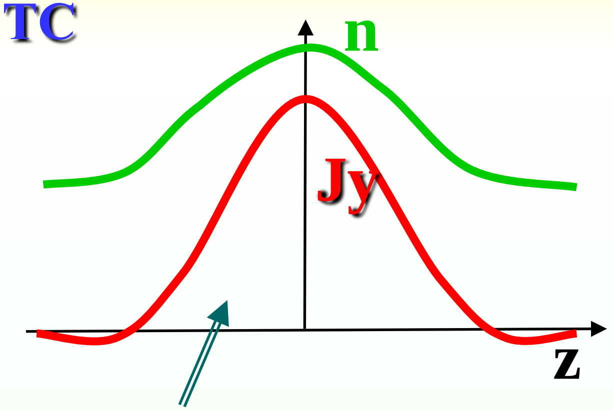
$$W_0 = const;\ \ I_z\ ;\ \ const$$

$$\Rightarrow \quad f_{p+,O+} \equiv f(v_{II}, v_\perp) \to f(W_0, I_z)$$

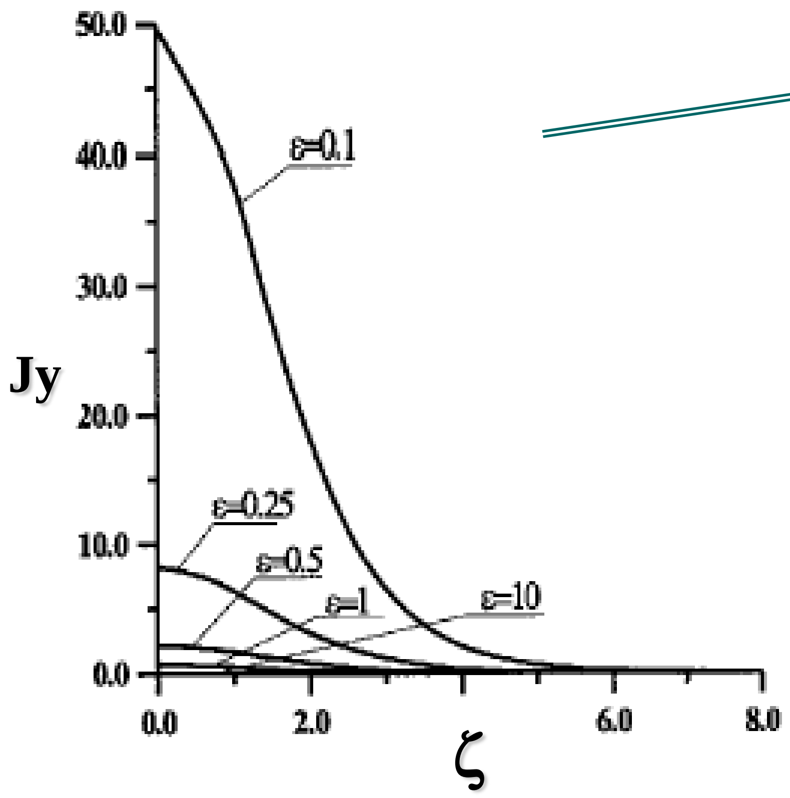
The distribution function $f_{trans,\ trap}$ can be presented as a function of integrals of motion $\{W_0, I_z\}$ and using Liouville theorem could be be calculated at all locations within CS

Равновесные решения в модели ТС без электронов: в них впервые получена вложенность тонкого токового слоя внутри более широкого плазменного слоя как основное свойство ТС

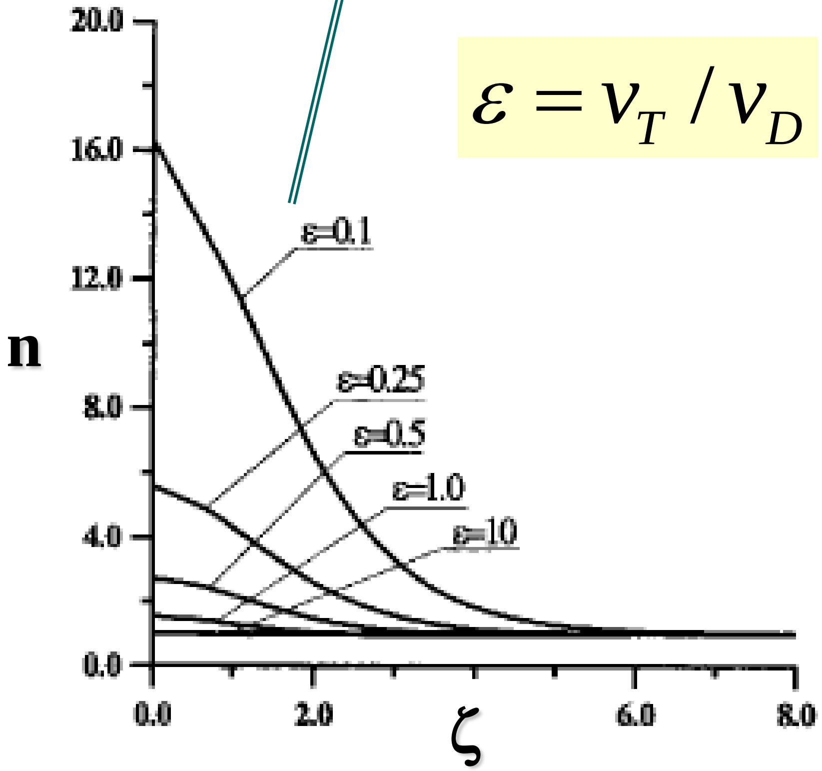
Полученное самосогласованное решение имело толщину порядка одного-нескольких протонных гирорадиусов во всем диапазоне параметров модели. Оценка ширины ТС зависела от отношения ε тепловой скорости протонов к их потоковой скорости.



Вложенный ТС



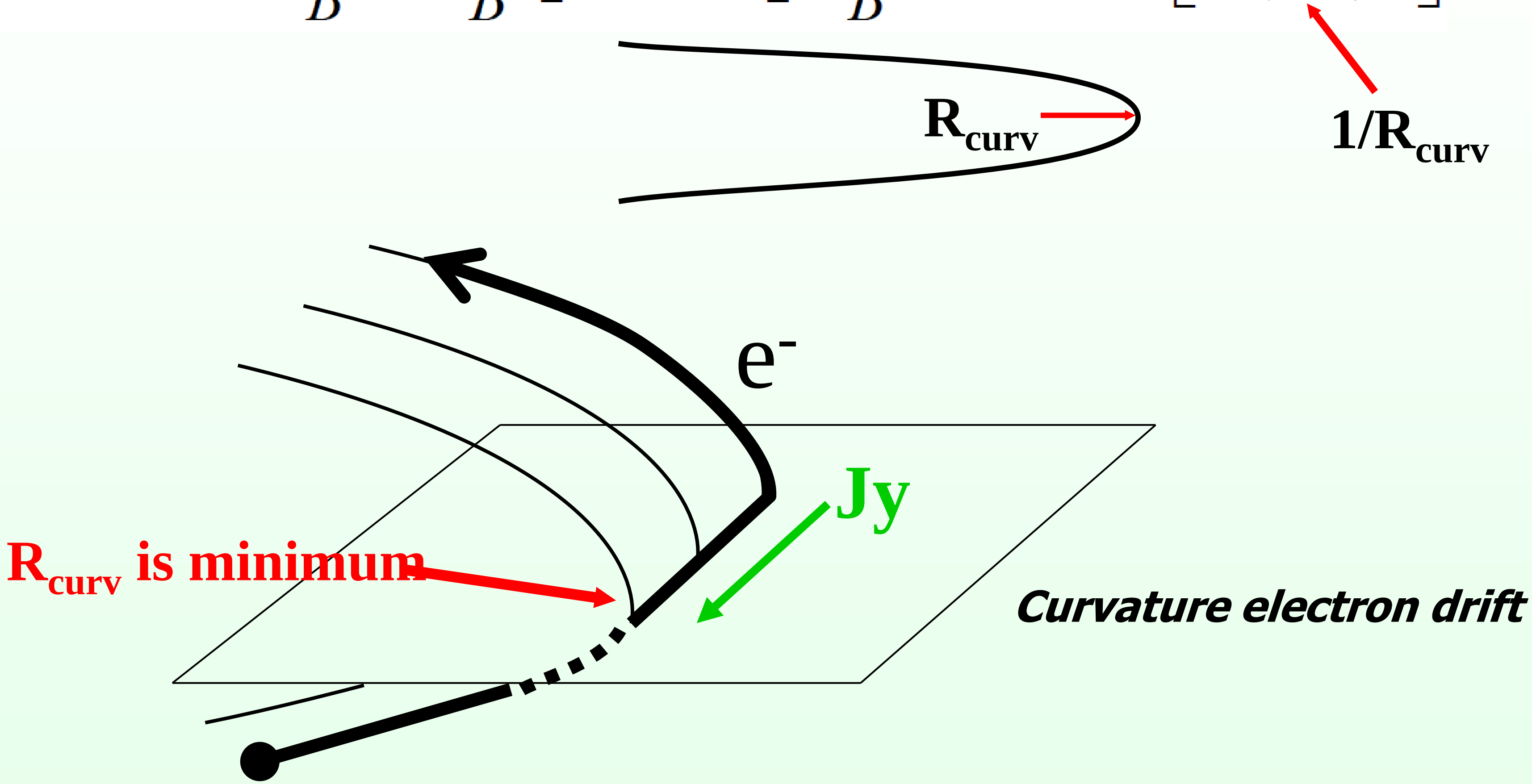
Zelenyi et al., NPG, 2000



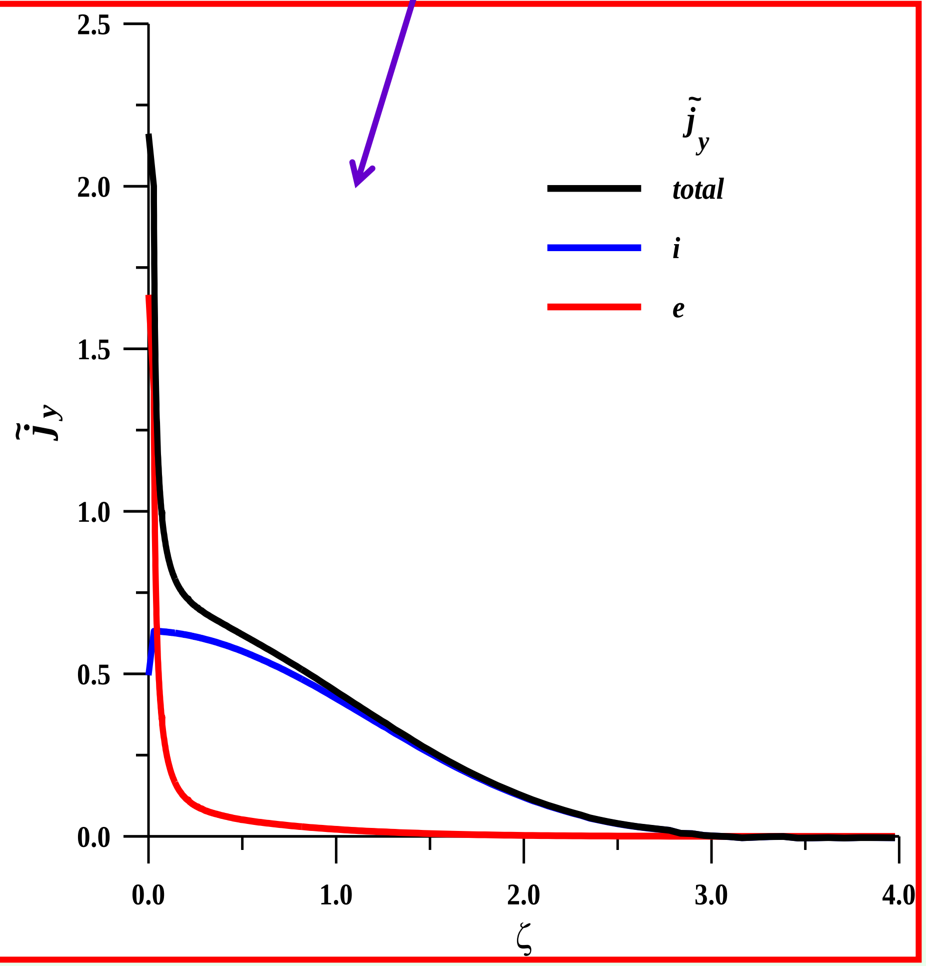
$$\varepsilon = v_T / v_D$$

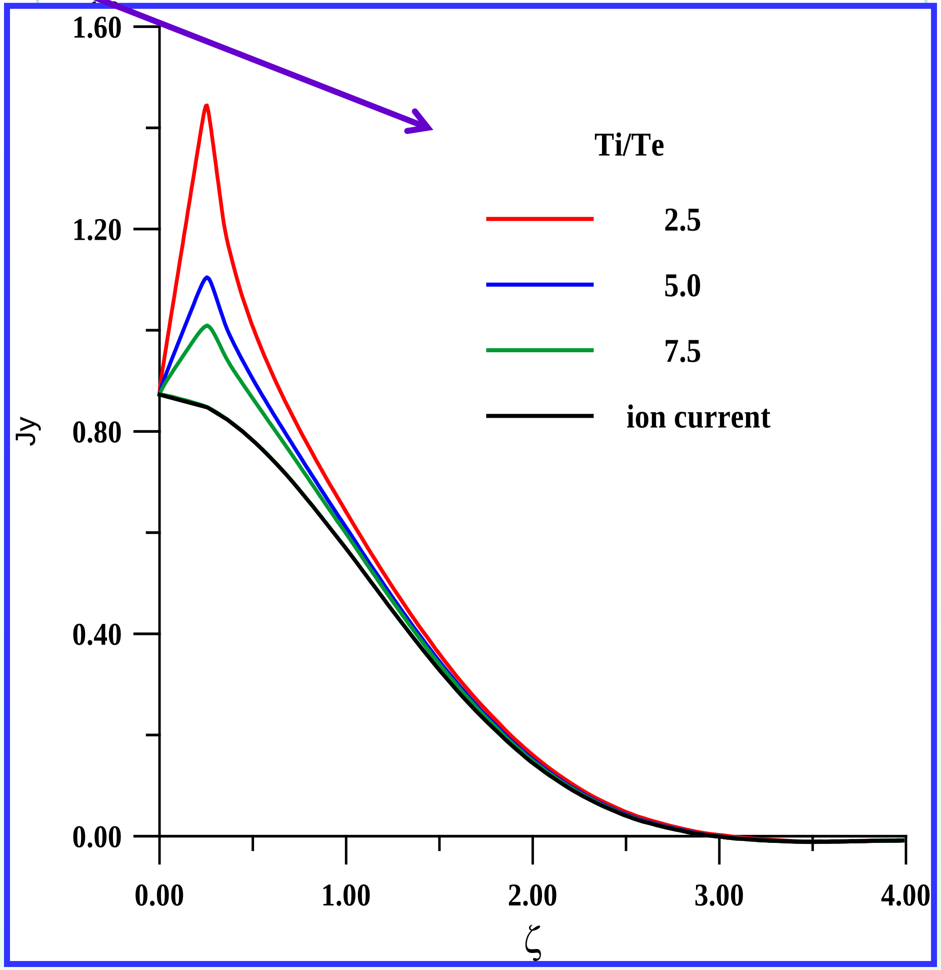
Электронные дрейфы кривизны в обращенном магнитном поле

$$J_{e\perp} = -e n_e c \frac{\left[\vec{E},\vec{B}\right]}{B^2} + \frac{c}{B^2}\left[\vec{B},\vec{\nabla}_\perp \tilde{p}_{\perp e}\right] + \frac{c}{B^4}\left(\tilde{p}_{\parallel e} - \tilde{p}_{\perp e}\right)\left[\vec{B},\left(\vec{B}\vec{\nabla}\right)\vec{B}\right]$$



Учет электростатических эффектов: профили самосогласованного ТТС в присутствии анизотропного и изотропного давления электронов





Zelenyi L. M., H. V. Malova, V. Yu. Popov, D. Delcourt, and A.S. Sharma, Nonlinear equilibrium structure of thin currents sheets: influence of electron pressure anisotropy, Nonlinear Processes in Geophysics, v. 11 , pp. 579-587, 2004

Масштабы толщин токовых слоев:

- **В модели Харриса толщина ТС может быть сколь угодно большой**

$$L = \frac{c}{\omega_{pi}} \frac{v_{Ti}}{u_i} \sqrt{\frac{T_i}{T_e + T_i}}$$

В модели ТТС масштаб зависит от параметра

$\varepsilon = V_T/V_D$ *и определяется протонным гирорадиусом*

ε<<1:

$L \approx \rho_D \varepsilon^{4/3} = \rho_T \varepsilon^{1/3}$

(Francfort and Pellat, 1976)

ε≥1: $L \approx \rho_T$

(Ashour-Abdalla, Zelenyi et al., 1994); $\rho_D = v_D/\omega_0$, $\rho_T = v_T/\omega_0$

Толщина электронного слоя:

➢ Half-thickness of electron inner sub-layer is estimated as $L_i \sim \delta_i \sim c/\omega_{pi}$; $\Rightarrow$ $L_e \sim \lambda \sim \delta_i^2/\rho_{in}$

толщина ТС с квазиадиабатической ионной динамикой имеет масштаб нескольких протонных гирорадиусов

Механизмы усложнения структуры ТТС:

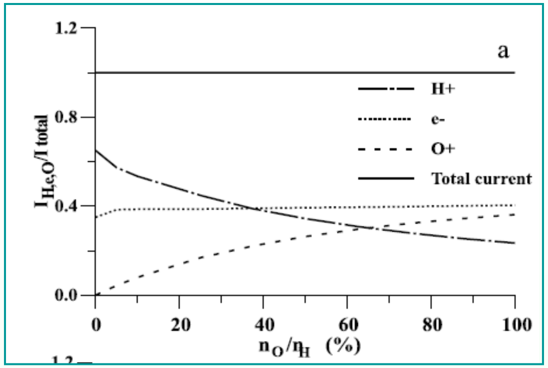
- <u>**Учет ионов кислорода и других тяжелых ионов**</u>
- **Влияние захваченных и квазизахваченных ионов**
- **Немаксвелловское распределение плазмы**
- **Наличие шировой компоненты магнитного поля By**

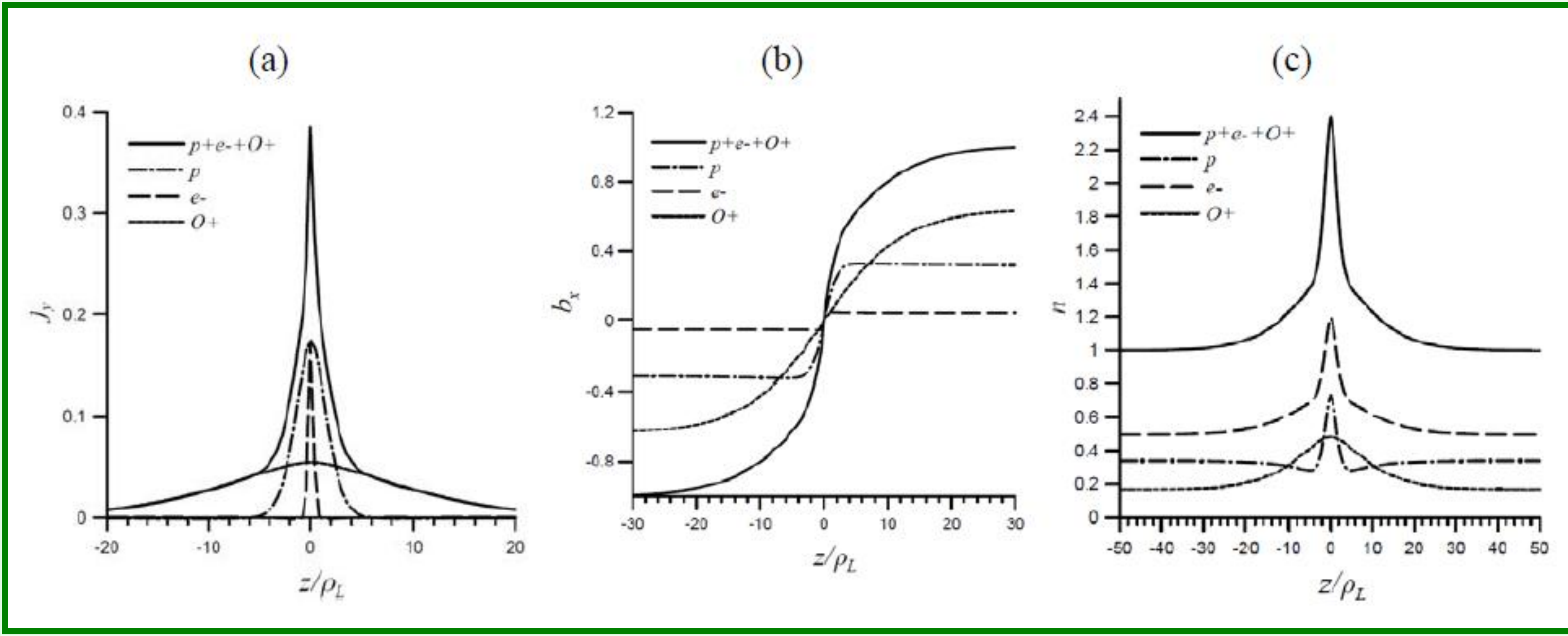
Zelenyi L. M., H. V. Malova, V.Yu. Popov, D. C. Delcourt, N. Yu. Ganushkina, A. S. Sharma, ”Matreshka” model of multilayered current sheet, GEOPHYSICAL RESEARCH LETTERS, VOL. 33, L05105, doi:10.1029/2005GL025117, 2006

Домрин и др, Геомагн.Аэрон, 2020

Структура токового слоя с тяжелыми ионами: тройное вложение токов

Zelenyi L. M., H. V. Malova, V.Yu. Popov, D. C. Delcourt, N. Yu. Ganushkina, A. S. Sharma, ”Matreshka” model of multilayered current sheet, GEOPHYSICAL RESEARCH LETTERS, VOL. 33, L05105, doi:10.1029/2005GL025117, 2006





Домрин и др, Геомагн.Аэрон, 2020

Модель многомасштабного вложенного токового слоя: Модель “Матрешки”

Sitnov, M.I., L.M. Zelenyi, H.V. Malova, and A.S. Sharma, Thin current sheet embedded within a thicker plasma sheet: self-consistent kinetic theory, J. Geophys. Res., v.105, N A6, 13029-13044, 2000.

Zelenyi L., Sitnov M.I., Malova H.V., Sharma A.S., Thin and superthin ion current sheets, Quasiadiabatic and nonadiabatic models. Nonlinear processes in Geophysics, v.7, p.127-139, 2000.

Zelenyi L. M., H. V. Malova, V.Yu. Popov, D. C. Delcourt, N. Yu. Ganushkina, A. S. Sharma, ”Matreshka” model of multilayered current sheet, GEOPHYSICAL RESEARCH LETTERS, VOL. 33, L05105, 2006

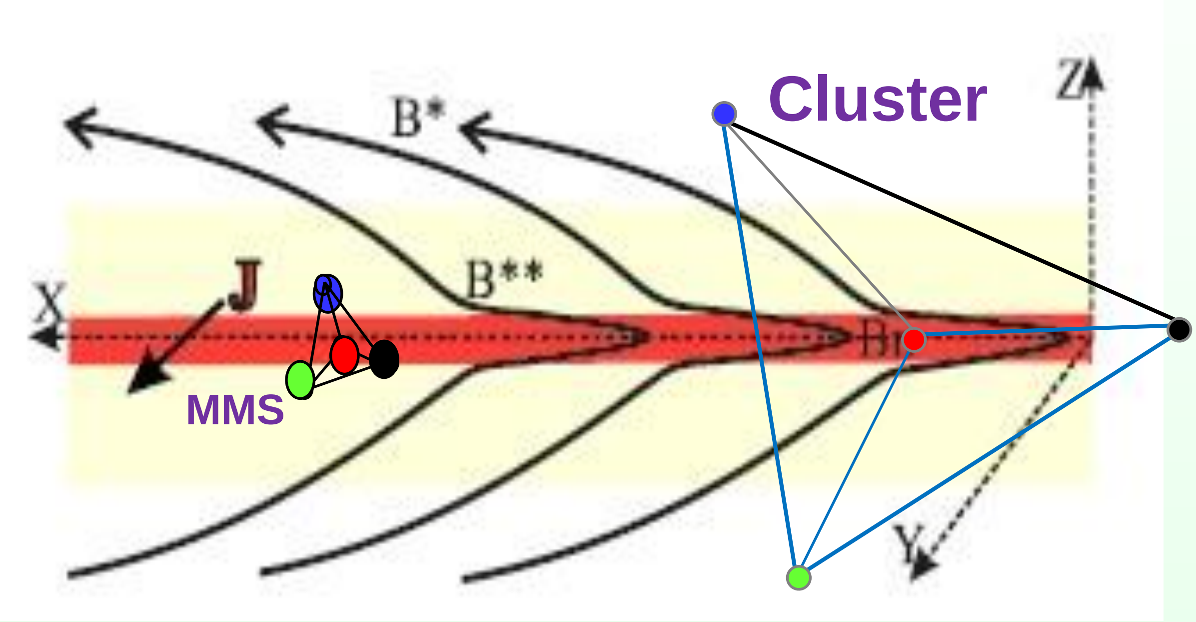
Zelenyi L.M., D. Delcourt, H.V. Malova, A. S. Sharma, V.Yu.Popov, A.A. Bykov, Advances in Space Research, v.30, N7, 1629-1638, 2002.

Zelenyi L.M., D.C. Delcourt, H.V. Malova, A.S. Sharma, "Aging" of the magnetotail thin current sheets, Geophys. Res. Lett., v.29, pp. 49-1 - 49-4, 2002.

Сравнение с данными спутников Cluster 2001-2004

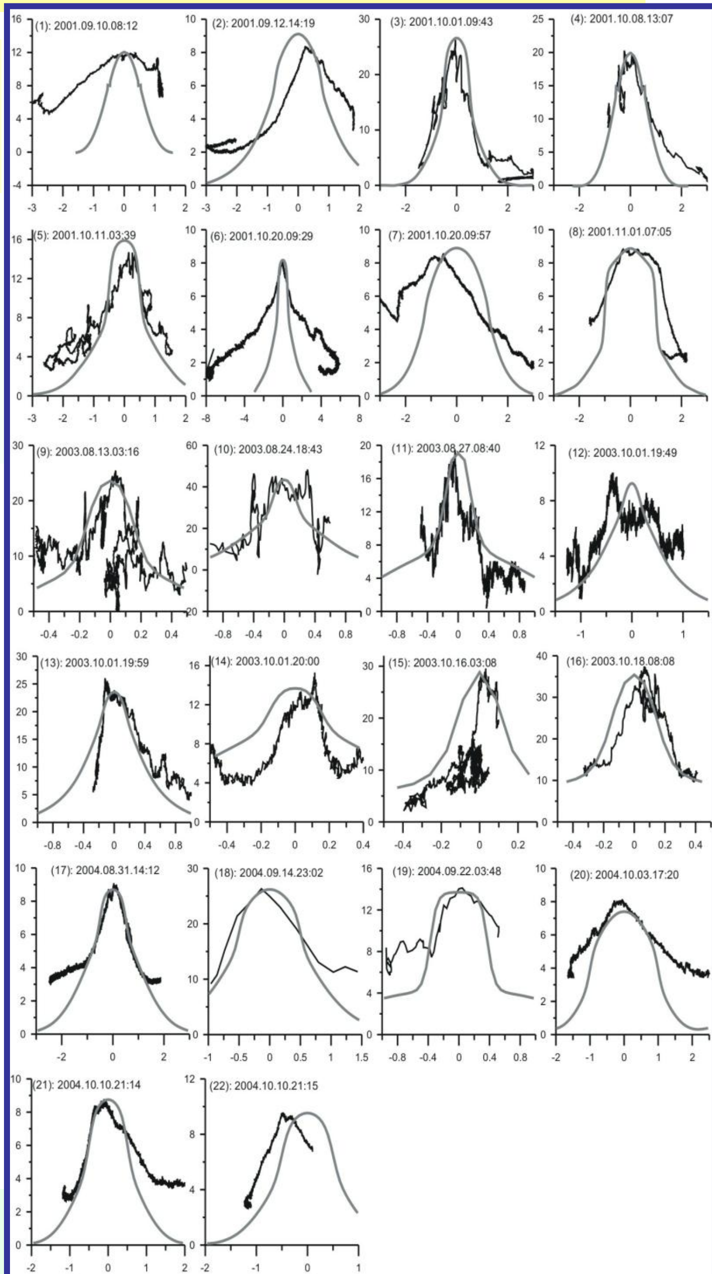
Artemyev A. V., A. A. Petrukovich, L. M. Zelenyi, H. V. Malova, V. Y. Popov, R. Nakamura, A. Runov, and S. Apatenkov, Comparison of multi-point measurements of current sheet structure and analytical models, Ann. Geophys., 26, 2749–2758, 2008.

While Cluster is capable to study the TCS at ion scales, MMS is successful in studies of STCS at electron scales



The method of comparison with experimental data

Artemyev A. V., A. A. Petrukovich, L. M. Zelenyi, H. V. Malova, V. Y. Popov, R. Nakamura, A. Runov, and S. Apatenkov, Ann. Geophys., 26, 2749–2758, 2008.



22 случая из данных Cluster (2001, 2003, 2004) выбраны для сравнения

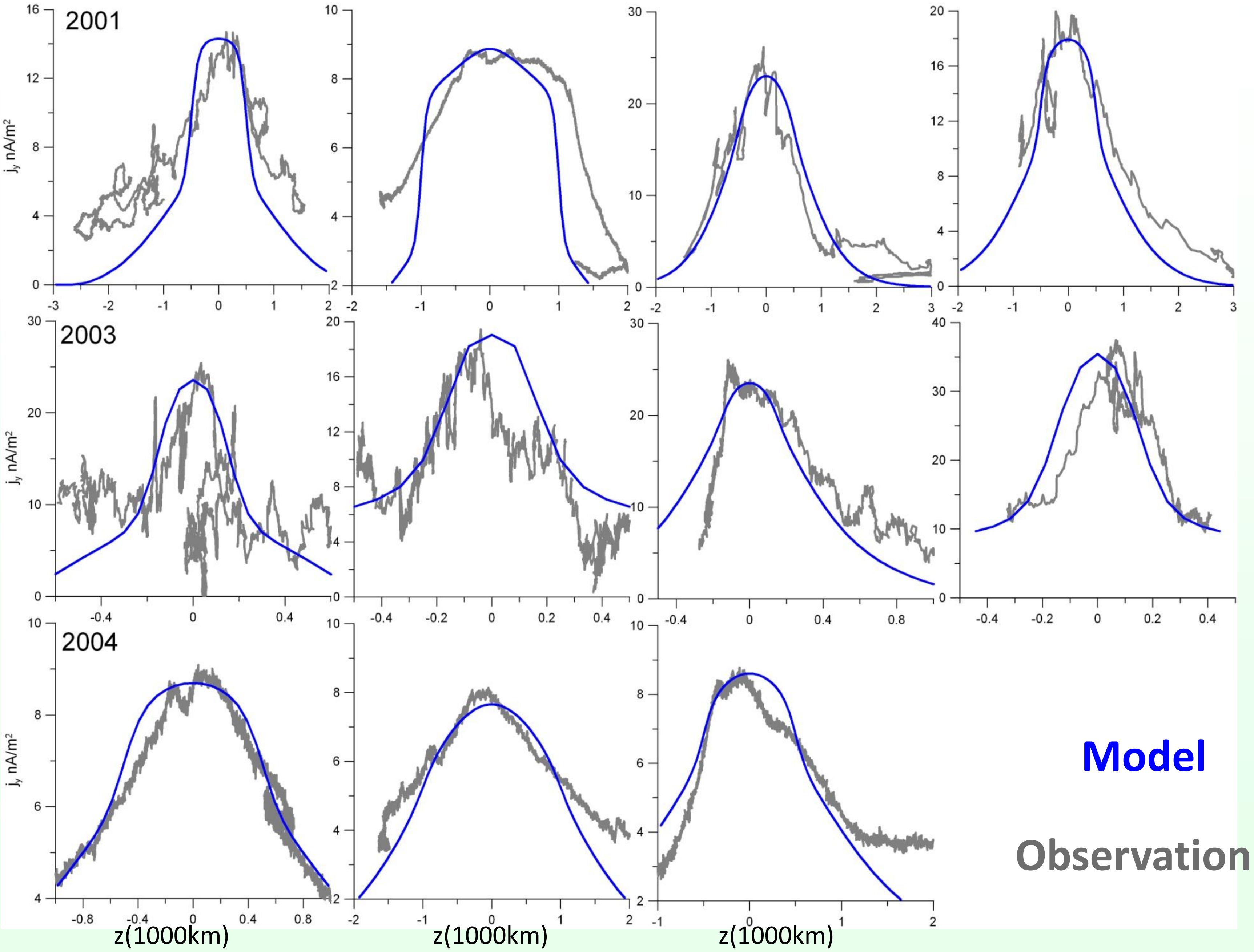
Для слоев с высоким содержанием ионов кислорода применена модель с учетом O+ (№ 5, 15 и 16)

Для двух-трехпиковых слоев применена модель с учетом захваченной плазмы № 3, 8, 10, 18, 19.

Для самых «толстых» слоев использована модель с двухтемпературной плазмой (№ 2, 6, 7, 9, 12-14, 17, 20-22).

Свободные параметры: v_T/v_D, B_n/B_0, T_i/T_e, n_o/n_i, $k, v_{T2}/v_{T1}$, n_{T1}/n_{T2}, q

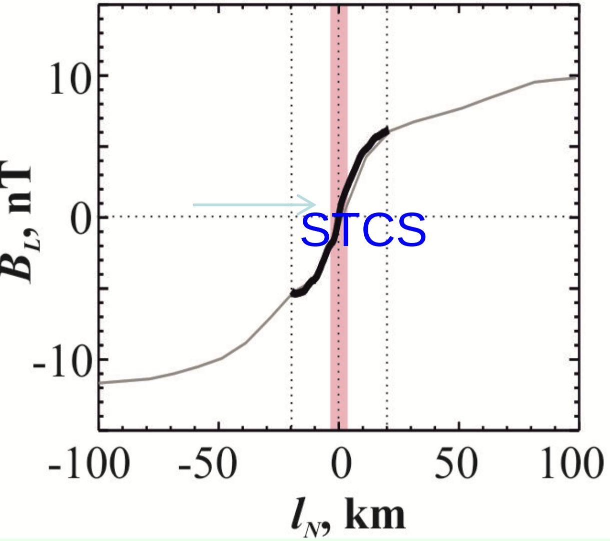
Comparison of CS model with observations



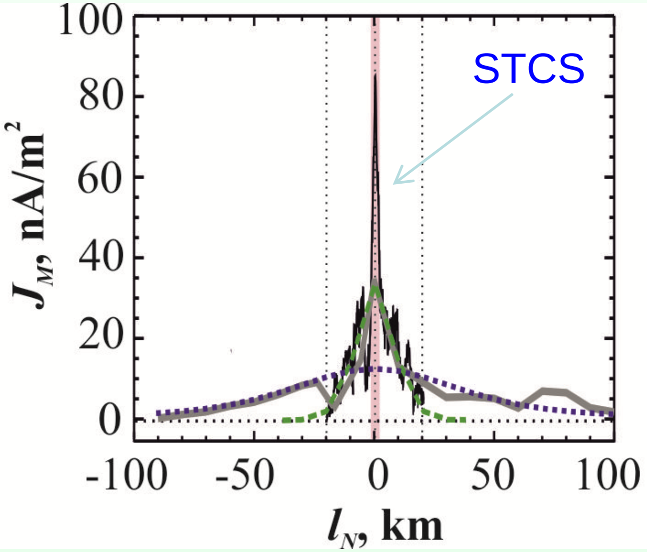
Super Thin Current Sheets (STCSs) of electron scales embedded into the ion layers

- Using high resolution magnetic field data from MAVEN we observe STCSs in the Martian magnetotail.
- The typical L_{STCS} is ≤ 5 km << ρ_p.
- The STCSs are embedded into a thicker sheet with $L \geq \rho_p$ forming a multiscale current configuration.
- The formation of STCS does not depend on ion composition and is controlled by the small B_N.

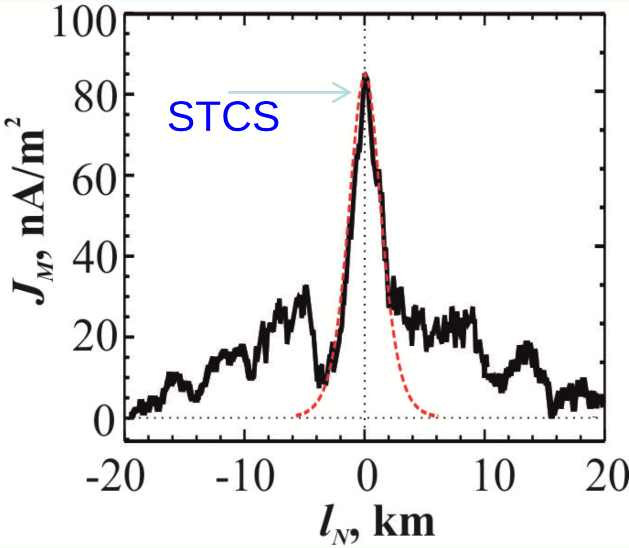
Spatial profile of the B_L field across the CS plane



Spatial profile of J across the CS plane



Zoom of spatial profile of STCS current density



(Grigorenko et al., GRL, 2019)

Universal scaling of thin current sheets (TCSs) in space plasma (Zelenyi et al., GRL, 2020)

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Geophysical Research Letters

RESEARCH LETTER
10.1029/2020GL088422

Key Points:
- Super thin electron current layers embedded into a thicker proton current sheet are described by a simple analytical model
- Magnetic field profile in electron layer revealed its nonlinear character
- Structure of electron layer and its scaling conform with MAVEN observations in the Martian magnetotail

Supporting Information:
- Figure S1
- Figure S2
- Figure S3
- Figure S4
- Figure S5
- Figure S6
- Figure S7
- Figure S8

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Zelenyi, L. M., Malova, H. V., Grigorenko, E. E., Popov, V. Y., & Dubinin, E. M. (2020). Universal scaling of thin current sheets. *Geophysical Research Letters*, *47*, e2020GL088422. https://doi.org/10.1029/2020GL088422

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Universal Scaling of Thin Current Sheets

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[1]Space Research Institute of the Russian Academy of Sciences, Moscow, Russia, [2]Department of Space Physics, Moscow Institute of Physics and Technology, Moscow, Russia, [3]Scobeltsyn Institute of Nuclear Physics of Lomonosov Moscow State University, Moscow, Russia, [4]Faculty of Business and Management, National Research University Higher School of Economics, Moscow, Russia, [5]Physical Faculty of Moscow State University, Moscow, Russia, [6]Max Planck Institute for Solar System Research, Göttingen, Germany

Abstract Thin current sheets (TCSs) with thicknesses about ion Larmor radii are widespread in space. It is important to describe their equilibrium structure allowing them to store and then explosively release the accumulated free energy. When ions are moving along quasi-adiabatic trajectories while magnetized electrons follow guiding center drift orbits, TCSs can be described within the framework of a hybrid approach. The thickness of the embedded electron sheet remains uncertain because of the scale-free character of electron motion. In this work, we propose a novel analytical model of the multilayer TCS that provides a universal expression describing the inner (embedded) electron sheet in dependence of TCS characteristics. An unusual property of the embedded electron layer revealed in this analysis is the nonlinear profile of the magnetic field in the inner layer: $B(z) \sim z^{1/3}$, which conforms excellently with MAVEN observations of 43 TCSs in the Martian magnetotail.

Plain Language Summary Current sheets (CSs) are widespread in nature. They accumulate magnetic energy and then quickly explosively release it due to fast magnetic reconnection. We revealed unusual properties of a very narrow electron layer within also rather thin ion current sheet. Electron physics has the primary importance for this problem for two reasons: (1) very thin but very intense election currents provide substantial contribution to CS free energy and (2) magnetized electrons provide the "rigidity" to magnetic field lines preventing the immediate onset of reconnection. Once electrons are magnetized in CS, their average motion can be described by guiding center drift approximation which is scale free, so there are some difficulties to estimate the thickness of the electron layer. We developed here simple analytical model that allowed to determine (1) spatial scales of the narrow electron CS embedded inside the wider proton current sheet and (2) unusual and never reported before profile of magnetic field ($B(z) \sim z$ in power 1/3) within the electron layer instead of generally assumed linear dependence $B(z) \sim z$. CS structure generally is maintained by the coupling of ion and electron effects. Theory predictions conform quite well with a numerous MAVEN observations of CS crossings in the Martian magnetotail.

1. Introduction

Thin current sheets (TCSs) with thicknesses about ion gyroradii play an important role in various space plasma configurations. Numerous satellite measurements in the near-Earth space (Baumjohann et al., 2007; Nakamura et al., 2008; Petrukovich et al., 2011; Runov et al., 2008; Sergeev et al., 1996; Shen, Rong, et al., 2008; Shen, Liu, et al., 2008), planetary magnetospheres (Grigorenko et al., 2017, 2019), laboratory experiments (Frank et al., 2008; Yamada et al., 2010), and astrophysical observations (Arons, 2011) indicate that these magneto-plasma structures are responsible for the processes of magnetic field energy accumulation and subsequent fast release (e.g., solar flares and magnetospheric substorms) due to beginning of fast reconnection processes (e.g., Zelenyi et al., 2011).

Schematic drawings of such current sheet structures (which, in fact, represent magnetic field reversals) in the terrestrial and Martian magnetotails are shown in Figure 1. Despite the drastic difference in scales and topology of these plasma configurations, both magnetospheres contain current sheets separating plasma domains with oppositely directed magnetic fields. Cross-tail currents have complicated multilayer kinetic geometry where electron-dominated super thin current structures (STCSs) are embedded in a TCSs with ion scales.

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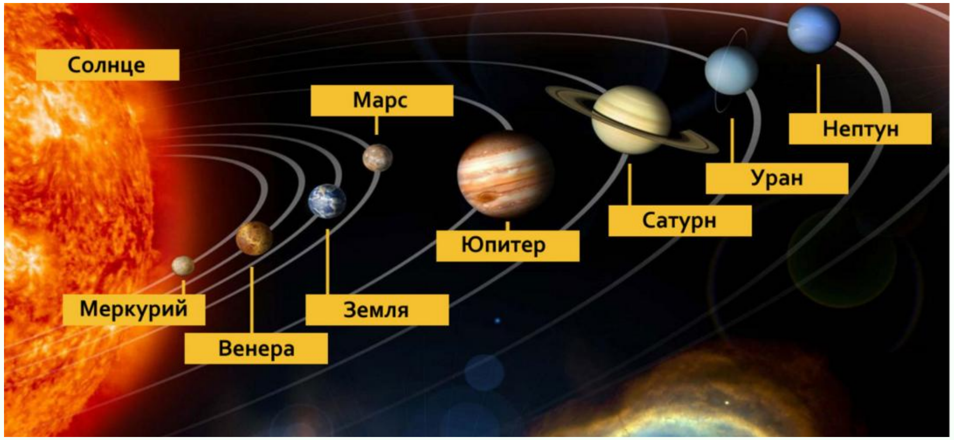
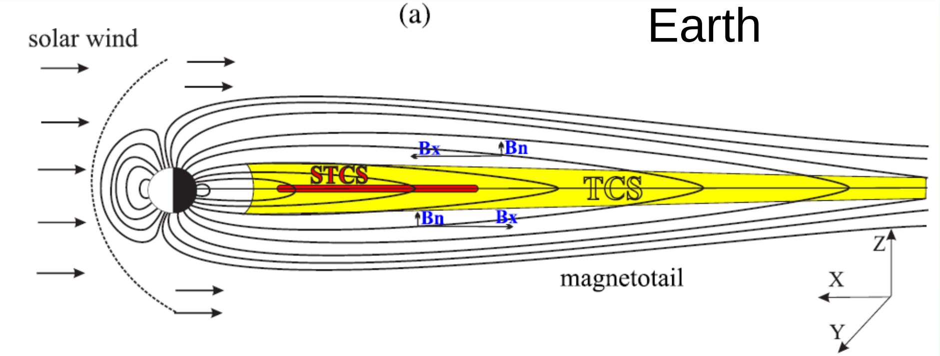
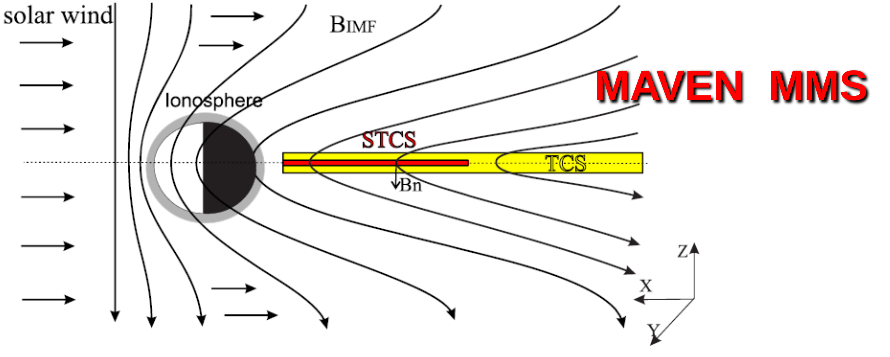


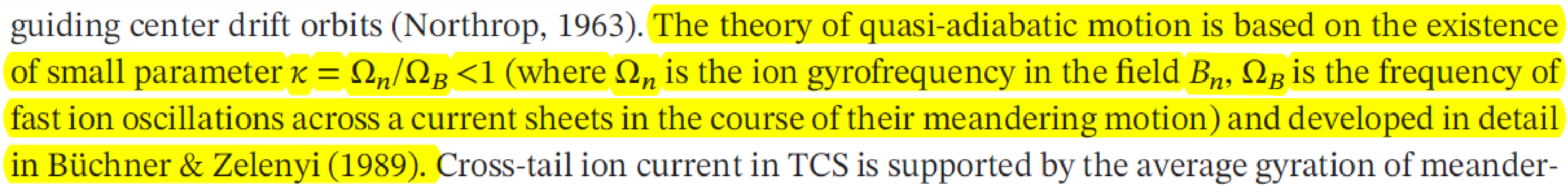


Новая генерация КА



MAVEN MMS

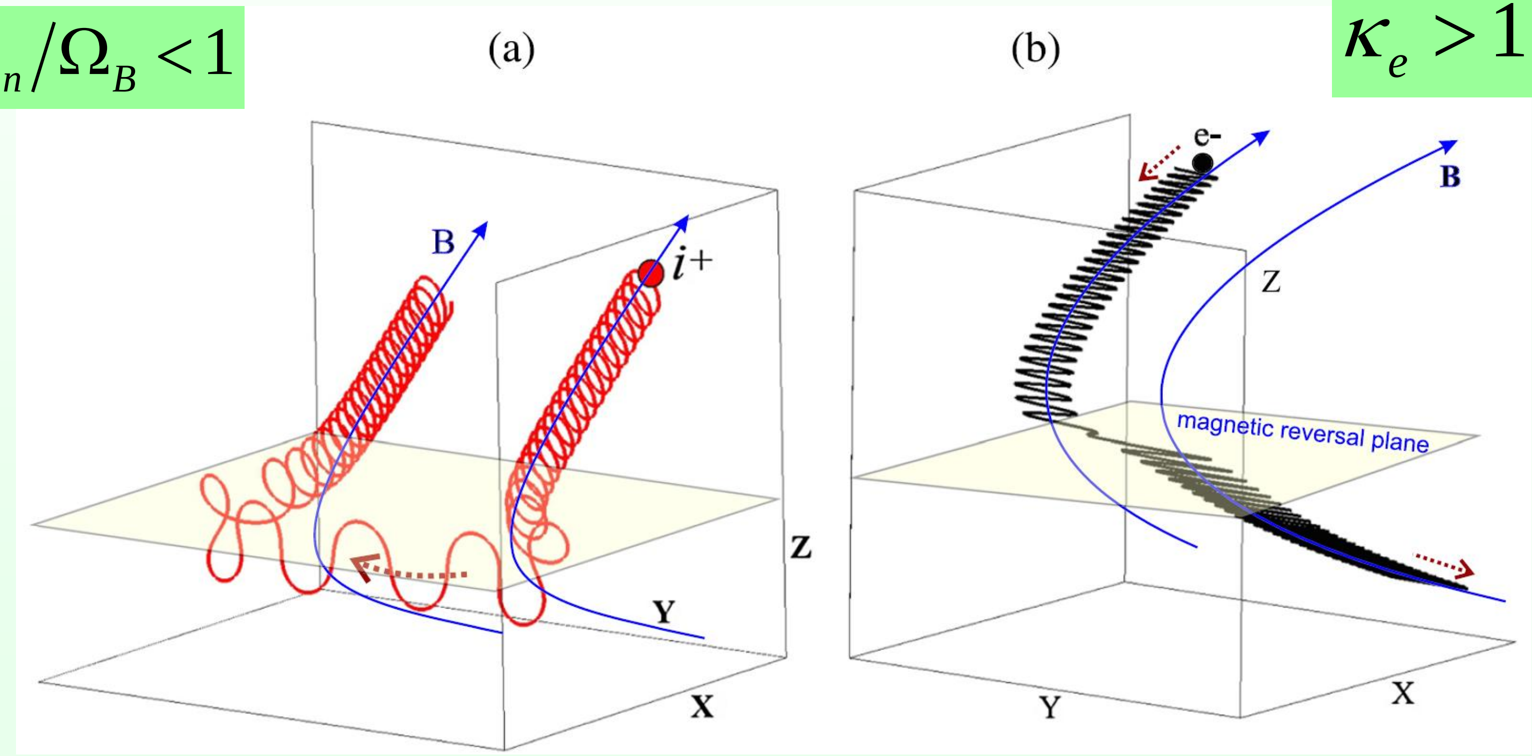
Динамика заряженных частиц в ТТС: квазиадиабатические ионы и замагниченные электроны



guiding center drift orbits (Northrop, 1963). The theory of quasi-adiabatic motion is based on the existence of small parameter $\kappa = \Omega_n/\Omega_B < 1$ (where Ω_n is the ion gyrofrequency in the field B_n, Ω_B is the frequency of fast ion oscillations across a current sheets in the course of their meandering motion) and developed in detail in Büchner & Zelenyi (1989). Cross-tail ion current in TCS is supported by the average gyration of meander-

$$\kappa = \Omega_n/\Omega_B < 1$$

$$\kappa_e > 1$$



SIMPLE 1D CONFIGURATION

$$\mathbf{B} = B_x(z)\mathbf{e}_\mathbf{x} + B_n\mathbf{e}_z$$

LOOKING FOR MAGNETIC FIELD PROFILE b(z)

$$\mathbf{j} = \mathbf{j}_i + \mathbf{j}_e \qquad rot\mathbf{B} = \frac{4\pi}{c}(\mathbf{j}_i + \mathbf{j}_e)$$

Here electron drift current is given by the expression (Krall and Trivelpiece, 1973)

$$\mathbf{j}_e = \frac{c}{B(z)}\left[\mathbf{h} \times \nabla_\perp p_{e\perp}\right] + \frac{c}{B(z)}\left(p_{e\text{II}} - p_{e\perp}\right)\left[\mathbf{h} \times (\mathbf{h}\nabla)\mathbf{h}\right]$$

$\mathbf{j}_e$

Here $p_{e\text{II}}$ and $p_{e\perp}$ are correspondingly parallel and perpendicular (with respect to magnetic field) components of diagonal electron pressure tensor; $\mathbf{h} = \mathbf{B}/|B|$, $B(z) = \sqrt{B_x^2(z) + B_n^2}$.

The maximum intensity of electron current is reached near the neutral plane where the gradient of electron pressure is small and curvature current, i.e. the last term Electron current Eq. strongly dominates:

$$\mathbf{j}_e \approx \frac{c}{B(z)}\left(p_{e\text{II}} - p_{e\perp}\right)\left[\mathbf{h} \times (\mathbf{h}\nabla)\mathbf{h}\right]$$

ELECTRON SCALES ARE ABSENT !!

Cross-tail current of demagnetized ions: $\mathbf{j}_i = en_i\mathbf{u}_i$

where $\mathbf{u}_i \sim v_{Ti}$ could be considered as characteristic velocity of ion motion

Входные параметры:

The normal magnetic field B_n

plasma density n

electron and proton temperatures T_e, T_i

These parameters determine two important spatial scales:

ion inertial lengths $\delta_i = \dfrac{c}{\omega_{pi}}$

where ω_{pi} is ion plasma frequency $\omega_{pi} = \sqrt{4\pi n_i e^2 / m_i}$

$\rho_{in} = v_{Ti} / \Omega_{in}$ - ion gyroradius in the field **Bn**

$\Omega_{ni} = eB_n / m_i c$ is ion gyrofrequency in B_n

ELECTRON SCALE FREE DESCRIPTION=THEN!
WHAT DETERMINES THE THICKNESS OF ELECTRON CURRENT LAYER??

One can introduce the dimensionless parameter $\eta = \delta_i / \rho_{in}$

which determines as we will see current sheet structure

Calculations of electron current due to strong curvature drift

Expression for electron current could be simplified to the following form:

$$\boxed{j_{ye}=\frac{c\Delta p_e B_n^4}{\{B(z)\}^6}\cdot\frac{dB_x(z)}{dz}}$$

where

$$\boxed{\Delta p_e = p_{\mathrm{P}e} - p_{\perp e}}$$

Therefore:

$$\boxed{rot\mathbf{B}=\frac{4\pi}{c}(\mathbf{j}_i+\mathbf{j}_e)} \longrightarrow \boxed{\frac{dB_x}{dz}=\frac{4\pi}{c}\frac{j_i}{\left(1-\frac{4\pi\Delta p_e B_n^4}{\{B(z)\}^6}\right)}}$$

Anisotropy of electron pressure tensor should satisfy the marginal firehose stability condition in TCS (Burkhart et al., 1992)

$$\boxed{\Delta p_e \equiv p_{e\mathrm{II}} - p_{e\perp} = \frac{B^2}{4\pi}}$$

Universal equation describing the embedded TCS

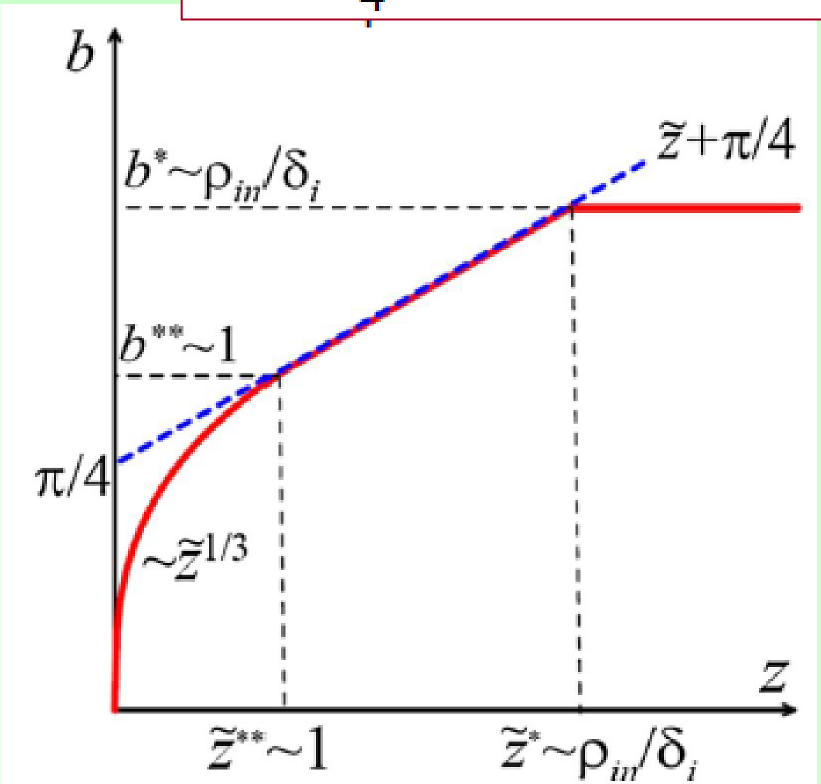
$$b(\tilde z)\left(1-\frac{1}{2\left(1+b^2(\tilde z)\right)}\right)-\frac{\operatorname{arctg} b(\tilde z)}{2}=\tilde z$$

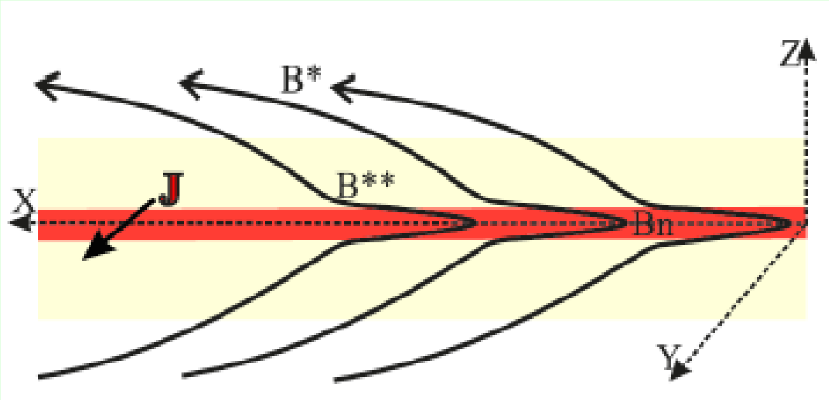
$$|\tilde z|<\tilde z^*$$

Asymptotic solutions in electron and ion dominated regions

1) $b(\tilde z)<1$ we can expand the left side of Eq. in Taylor series $\Rightarrow$ $b\approx\left(\frac{3}{2}\tilde z\right)^{1/3}, \ |\tilde z|\le\tilde z^{**}$

2) $b>1$ $b\approx\tilde z+\frac{\pi}{4};\quad \tilde z^{**}\le\tilde z\le\tilde z^{*}$ $\qquad b\approx\tilde z-\frac{\pi}{4};\quad -\tilde z^{**}\le\tilde z\le-\tilde z^{*}$





$$L_e\sim\lambda\sim\delta_i^2/\rho_{in}$$

Characteristic scale of the electron current ~ 3-10km

SUPER THIN CS

Comparison between theory and MAVEN observations

High resolution magnetic field observations by MAVEN (Connerney et al, 2015) have revealed the presence of TCS near the neutral plane (BX = 0) of the cross-tail current sheet at the nightside of Mars.

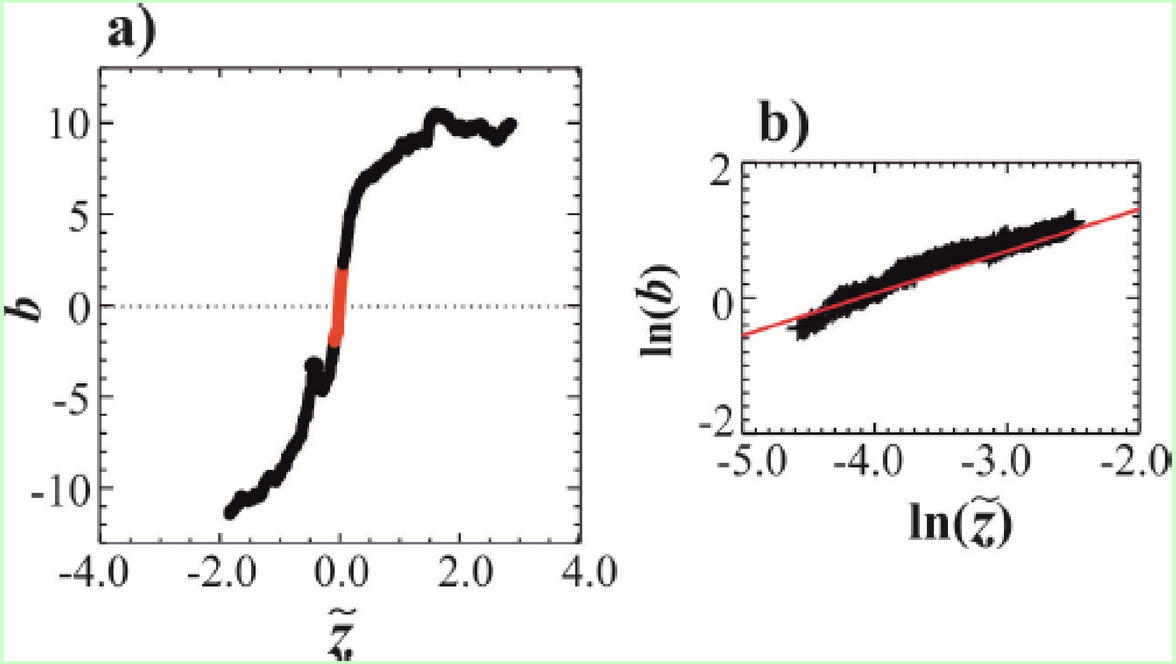


Figure (a) The spatial profile of b versus $\tilde{z}$ for the TCS crossing by the MAVEN spacecraft on 3 December 2014 between 16:05 and 16:07 UT. The STCS observed near the central plane ($B_L^* \sim 0$) is plotted in red. (b) The plot of $ln(b)$ versus $ln(\tilde{z})$ observed within the STCS. The best linear fit: $ln(b) \sim A \cdot ln(\tilde{z})$ where $A \sim 0.31$ is plotted in red.

Observational probability as a function of the power index b(z) ~ Z in power A

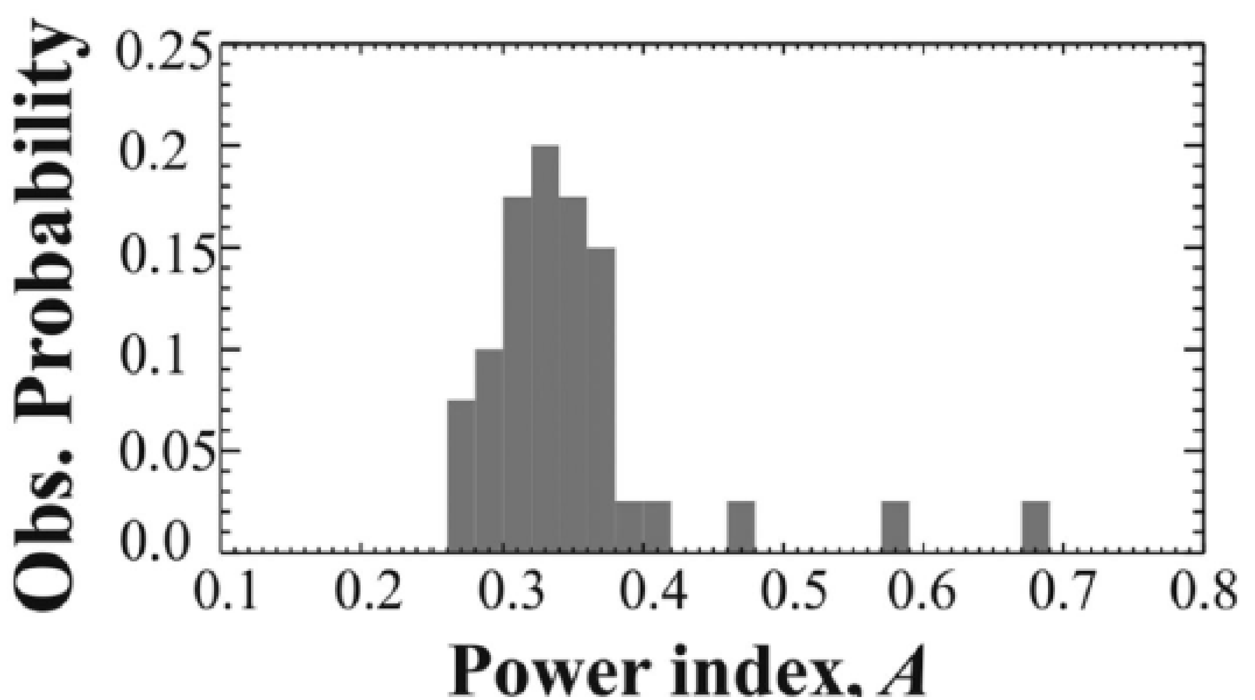
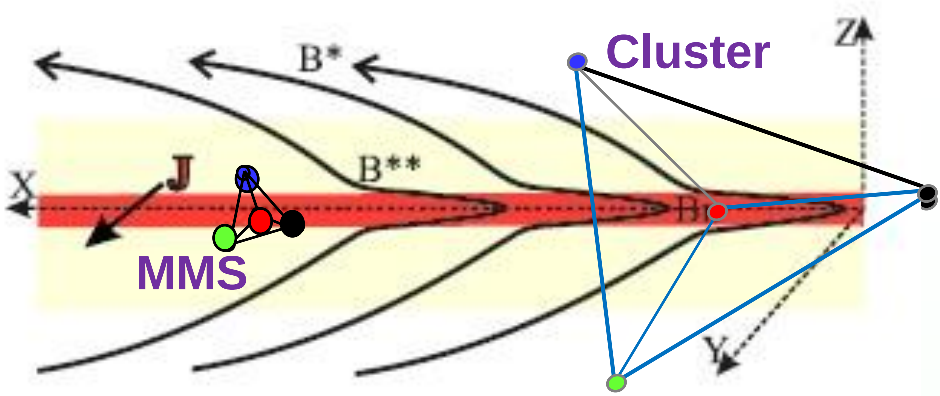


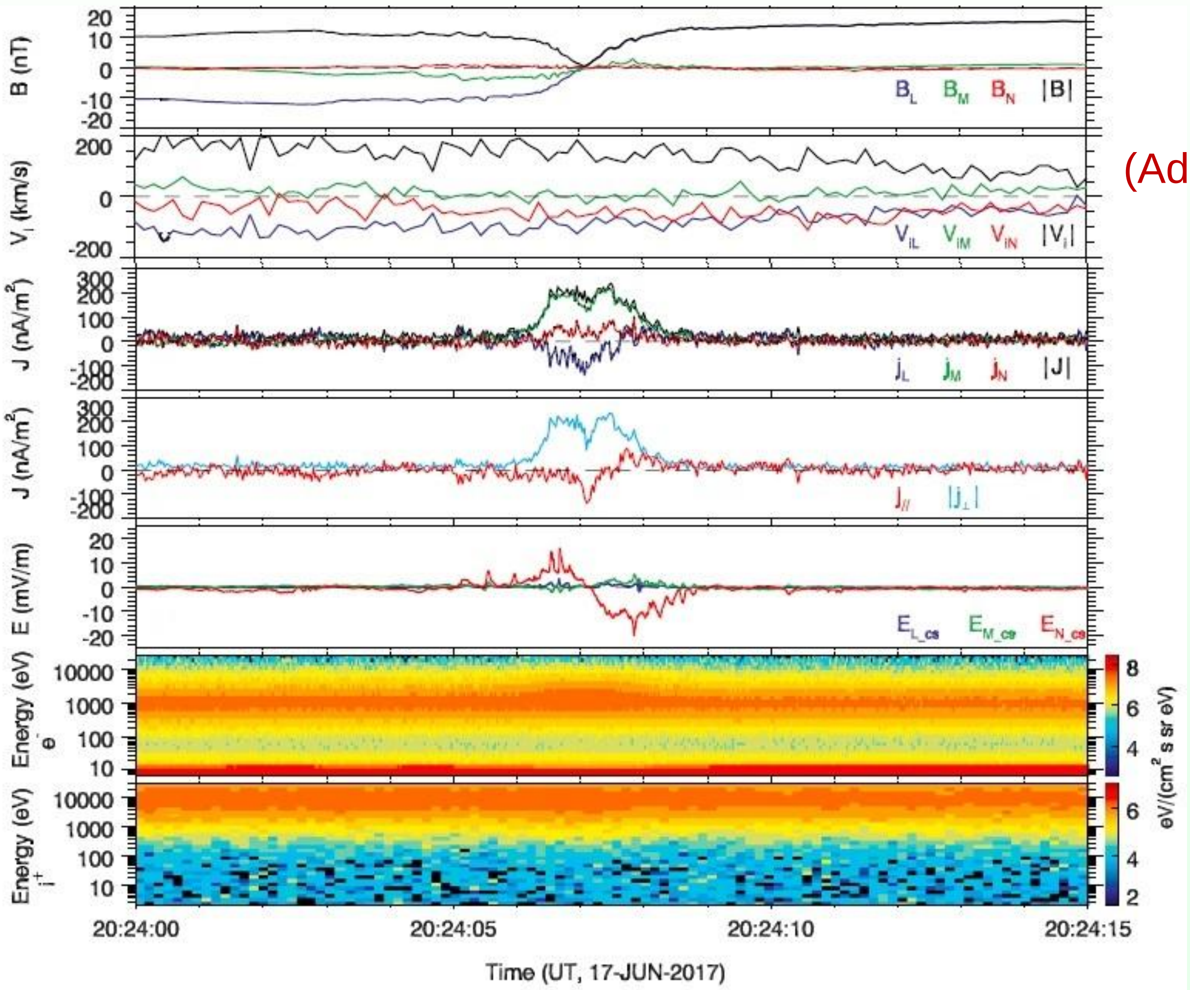
Figure The distribution of probability to use a given *A* value for the best linear fit of the *ln*(*b*) versus the *ln*(*z*) observed in each STCS from our database.

For each TCS we determine the value of *A*, and in Figure 5 we plot the distribution of probability to have a given *A* value for the best linear fit of the $ln(b)$ versus the $ln(\tilde{z})$

The distribution maximizes at *A* ~ 0.33 which corresponds well to the theory prediction. Thus, we may conclude that, contrary to all popular current sheet models, STCS has an unusual nonlinear magnetic field profile and cannot be described by the simple linear function of spatial coordinate ($\tilde{z}$), but can be fitted by the power law function of $\tilde{z}^A$ with *A* close to 0.33.



While Cluster is capable to study the TCS at ion scales, MMS is successful in studies of STCS at electron scales

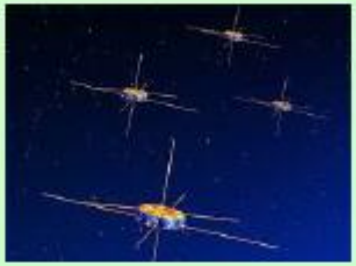


(Adapted from *Wang et al., GRL, 2018*)

MMS observations f electron-scale STCS

WORK IN PROGRESS

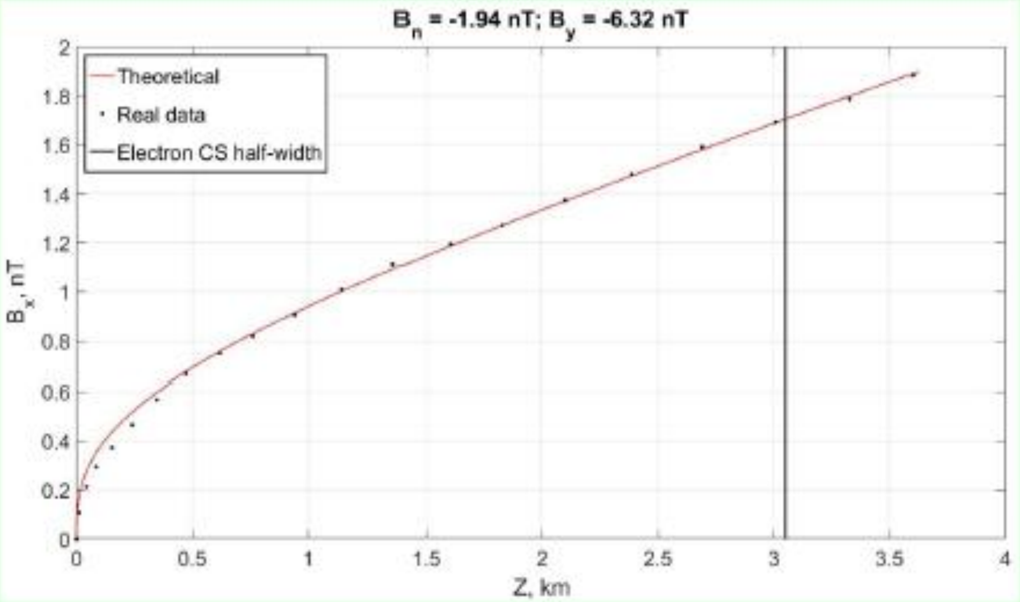
TCS CROSSING ANALYSIS USING -MAGNETOSPERIC MULTISCALE (MMS) DATA

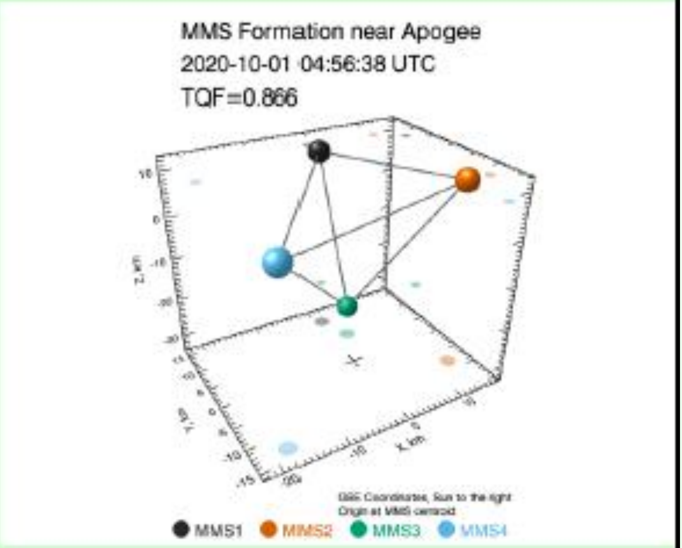


MMS

STCS can be observed only by high resolution ~ms magnetic field measurements.

In the Earth magnetotail MMS observations are capable to resolve STCS.





$L_{STCS} \sim 3$ km ($\sim \rho_e$)

СУПЕР ТОНКИЕ (единицы км) ТОКОВЫЕ СЛОИ

- Modern high resolution measurements (MMS, MAVEN, …..) provide remarkable looking glass to resolve extremely fine structures (few km). CSs usually have multilayered structure with super thin electron sheets embedded into much thicker proton(or oxygen) CS which provides to such multilayered CSs additional margin of a free energy

➢ Magnetic field observations demonstrate very good correspondence to our result concerning nonlinear magnetic field profile for any realistic value of magnetic shear

- Half-thickness of the outer ion sub-layer is estimated

$$\boxed{L_i \sim \delta_i \sim c/\omega_{pi}}$$

- Half-thickness of electron inner sub-layer is estimated

(not electron Larmor radius as usually assumed)

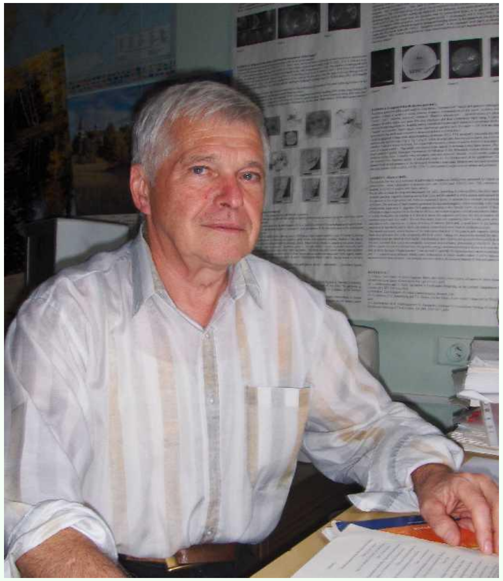
$$\boxed{L_e \sim \lambda \sim \delta_i^2/\rho_{in}}$$

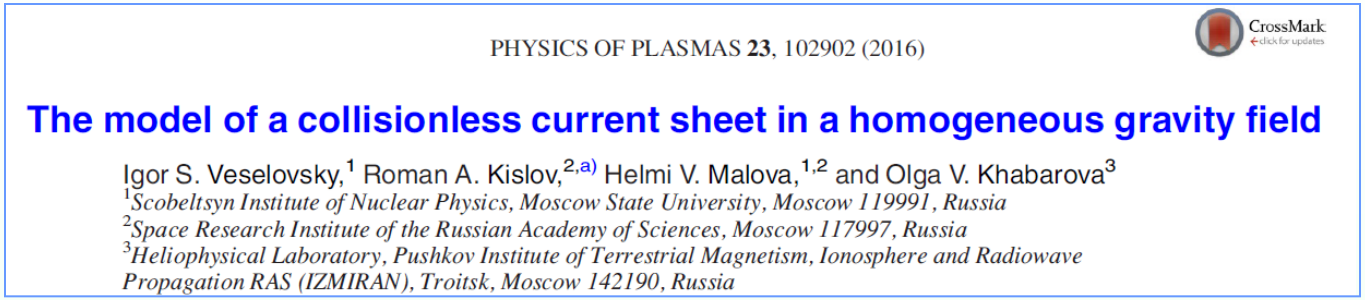
$$\boxed{b_x \approx \left(\frac{3 j_0 \cdot z}{\cos^2 \alpha}\right)^{1/3} \quad : \quad z^{1/3}}$$

Выводы

- Работы по исследованиям токовых структур в бесстолкновительной плазме, начатые в 60-е - 70-е годы в работах С.И.Сыроватского , Б.А. Тверского, В.П. Шабанского были продолжены в рамках совместных работ, проводимых командами ИКИ РАН, НИИЯФ МГУ, ПГИ, Измиран.
- Построенные теоретические модели согласуются с данными наблюдений и позволяют не только интерпретировать, но также и предсказывать новые физические свойства токовых структур в в космосе.

Памяти наших ушедших товарищей: последние совместные публикации НИИЯФ – ИКИ по токовым слоям и динамике частиц





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The model of a collisionless current sheet in a homogeneous gravity field

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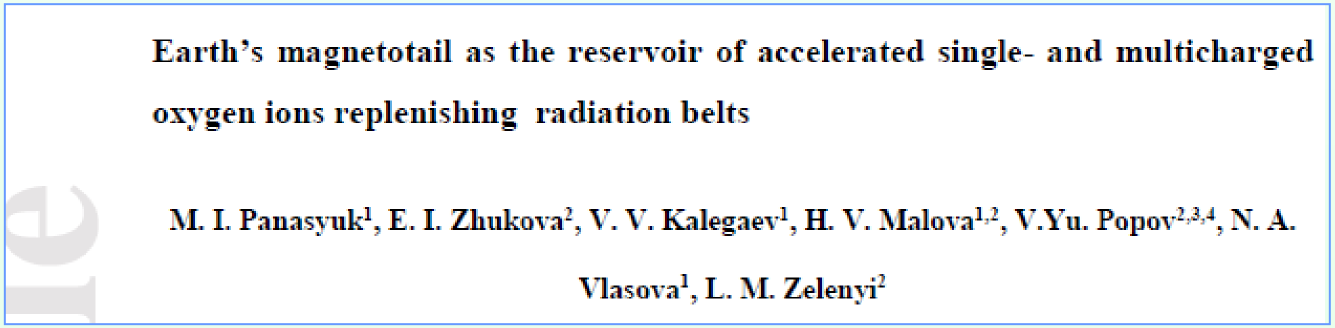

Earth's magnetotail as the reservoir of accelerated single- and multicharged oxygen ions replenishing radiation belts

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- Спасибо за внимание!

Поздравляем НИИЯФ МГУ с 75-летием!