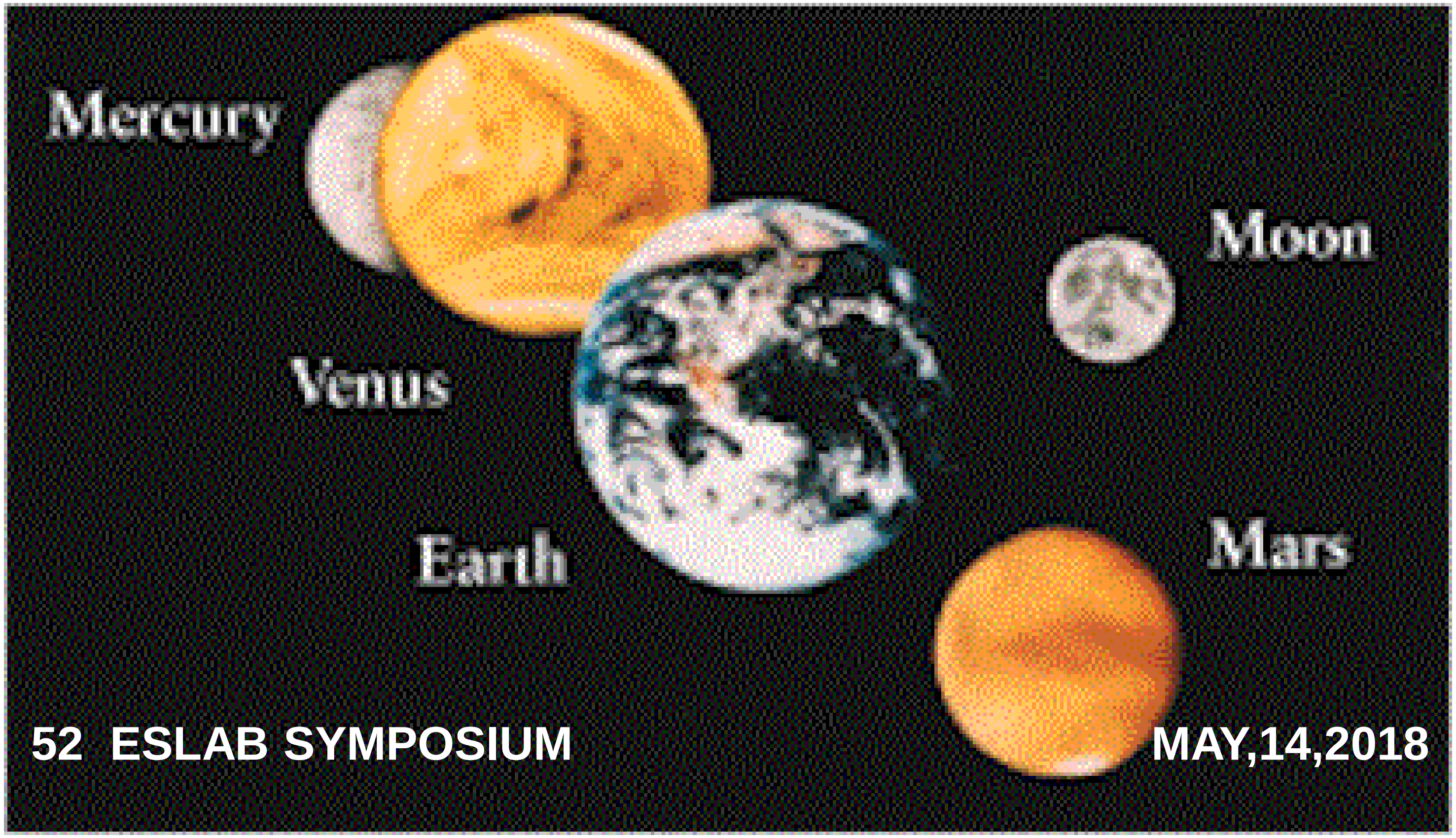
# Magnetospheres of Planets in the Inner Solar System.

***Sixty Years of the Space Age - Lessons Learned***

*LEV ZELENYI (IKI RAS)*



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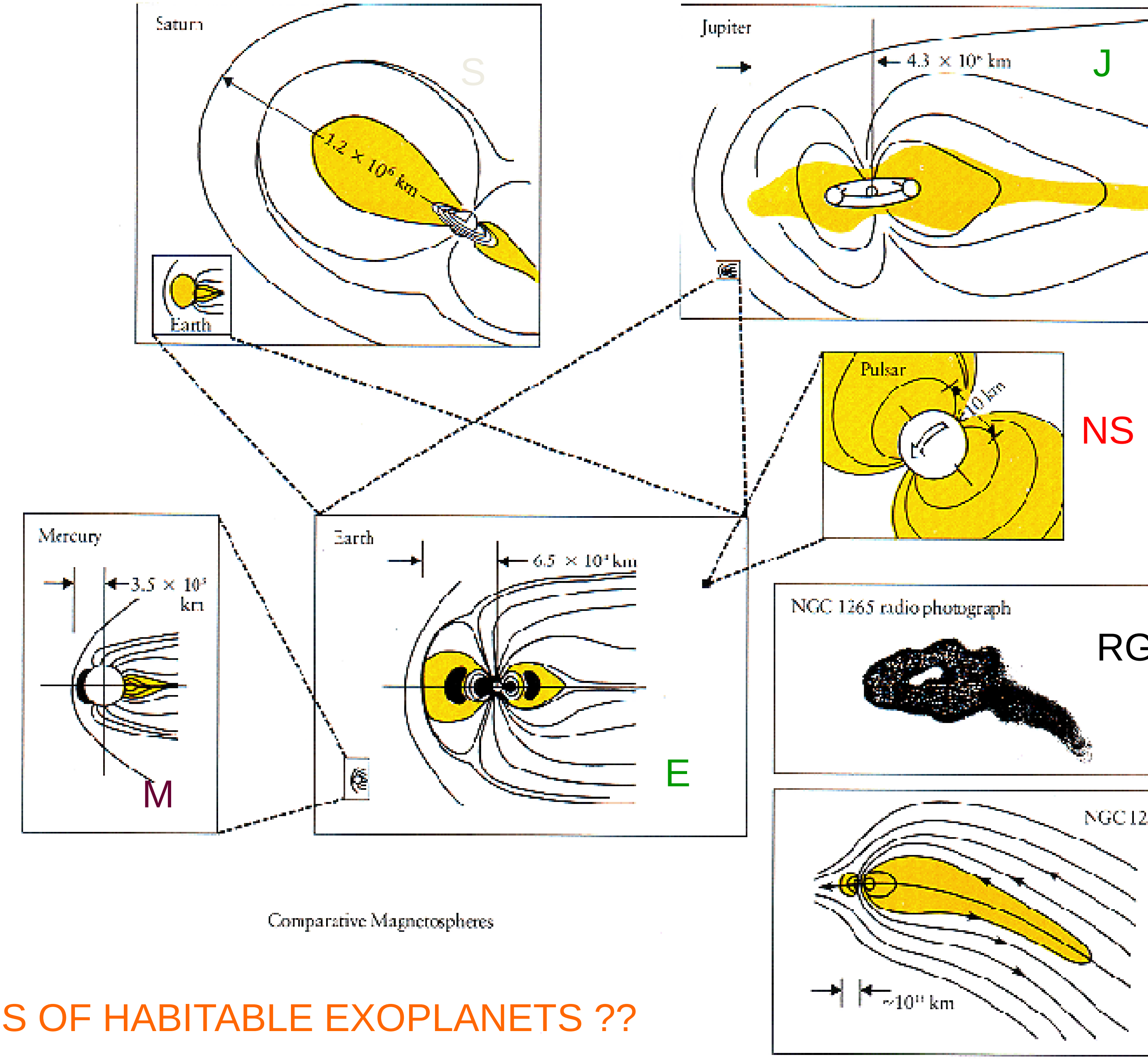
UNIVERSALITY OF MAGNETOSPERIC TYPE INTERACTIONS

+SCALING FACTOR

*HIERARCHY OF MAGNETOSPERIC SCALES*

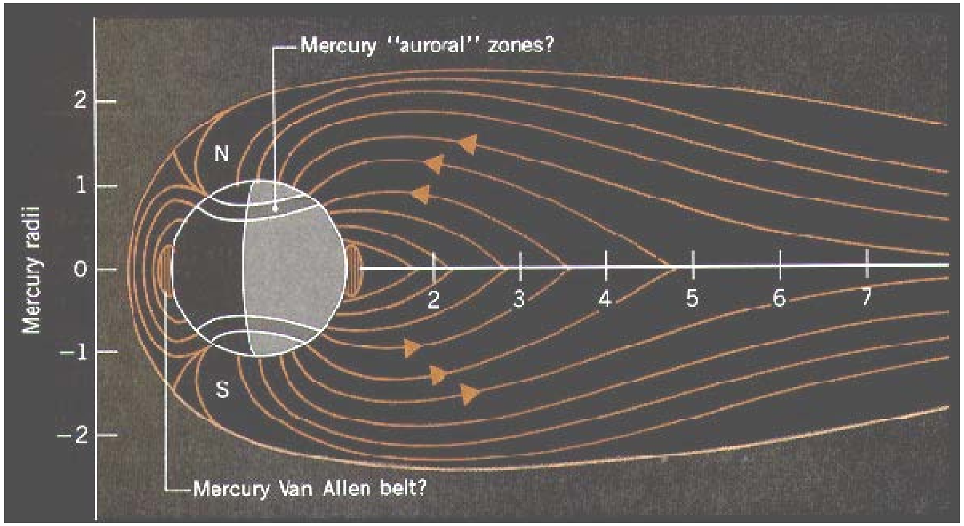



Comparative Magnetospheres

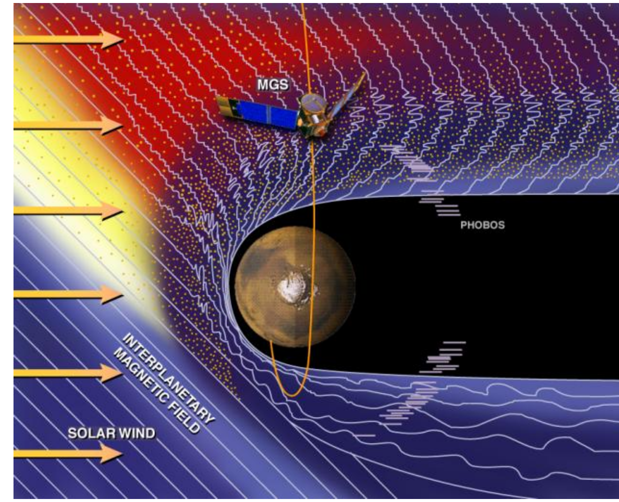
MAGNETOSPERES OF HABITABLE EXOPLANETS ??

# MAGNETOSPHERES OF PLANETS IN THE INNER SOLAR SYSTEM

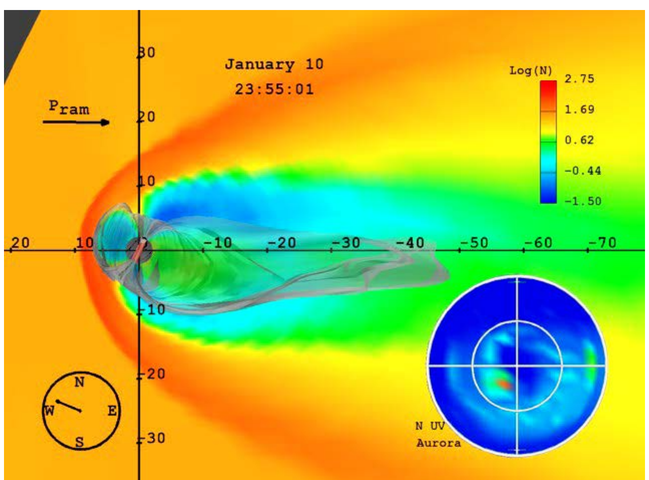
## MERCURY



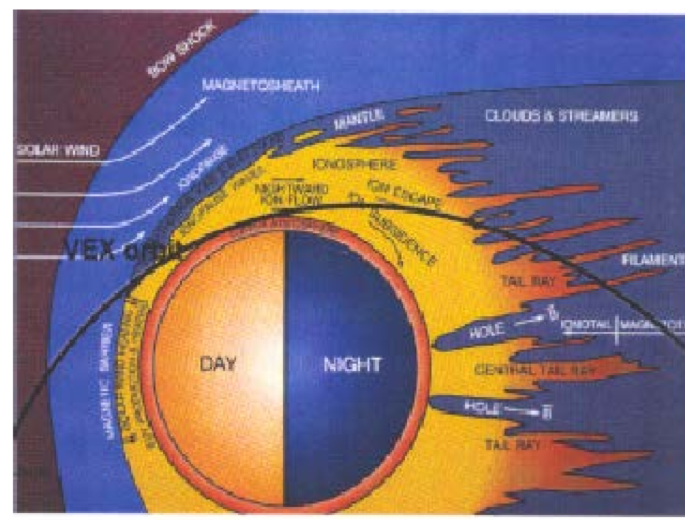

## MARS




## EARTH




## VENUS

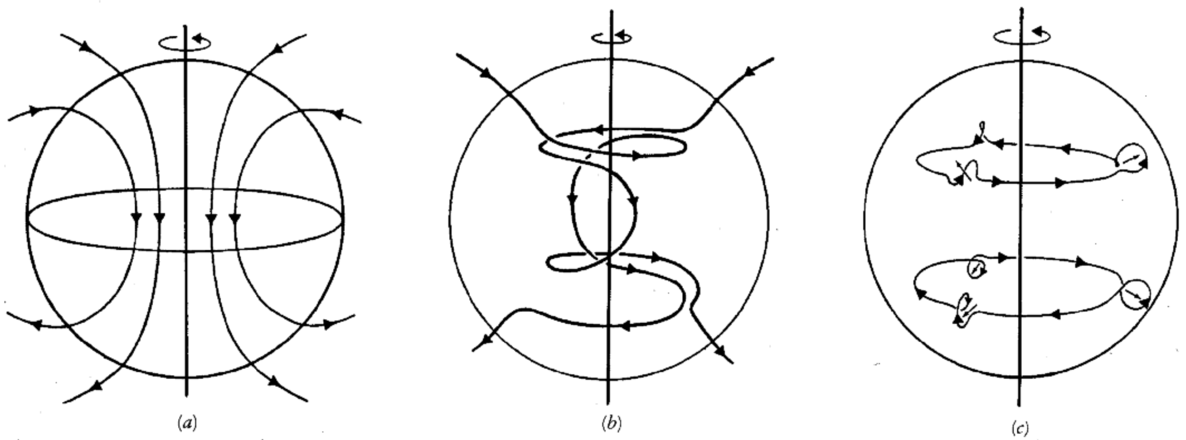


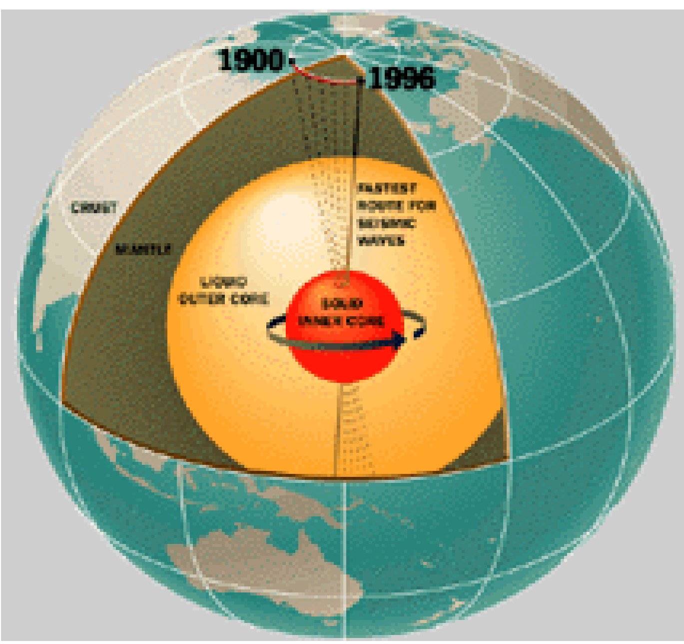
# INNER PLANETS OF SOLAR SYSTEM

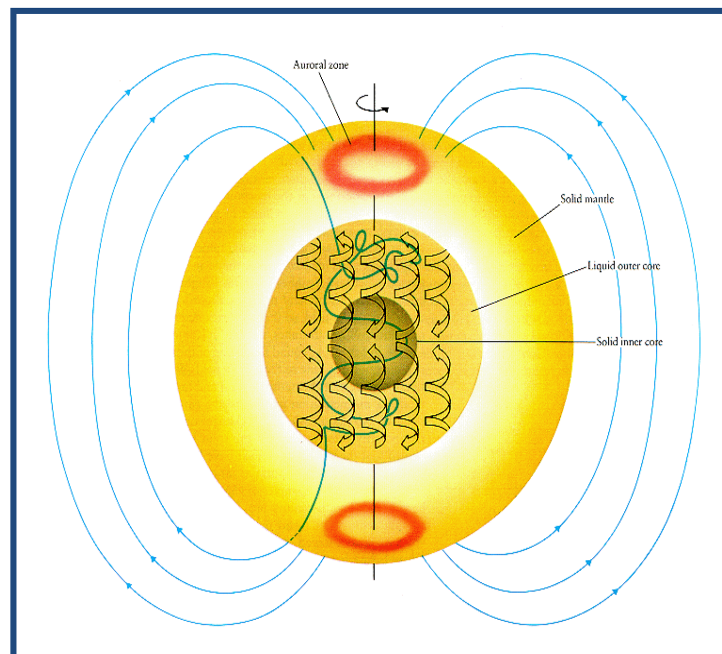
**>> all possible types of interaction <<**

| PLANET | MAGNETIC FIELD | | IONOSPHERE |
|---|---|---|---|
| MERCURY | + | | - |
| VENUS | - | | + |
| EARTH | + | | + |
| MARS | + | - | + |

# MAGNETIC FIELD GENERATION BY CONVECTIVE MOTIONS OF CONDUCTING MEDIA



# EARTH-Paleomagnetic

Terrestrial magnetic field changed its orientation 100-s times for last 160 millions years
Each inversion lasts~1000-6000 years and B was strongly decreased

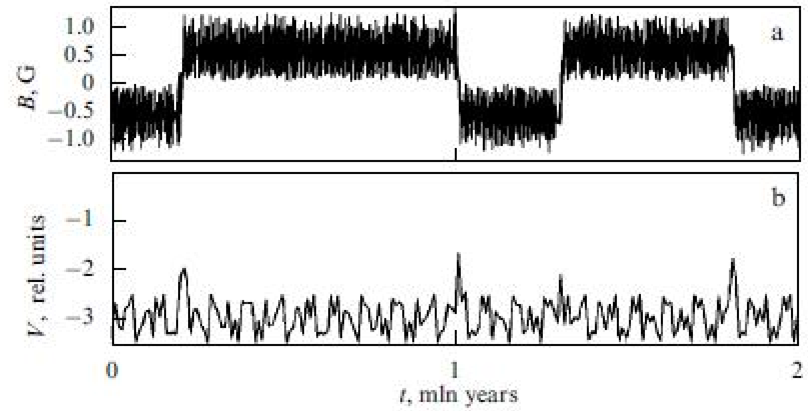
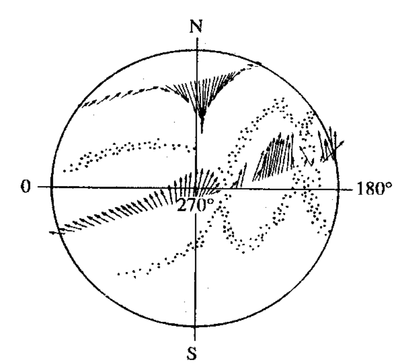



**Figure 2.** Mean dipole magnetic field strength on Earth's surface (a) and the velocity of the meridional motion of matter (b) as a function of time for the chaotic inversion regime.

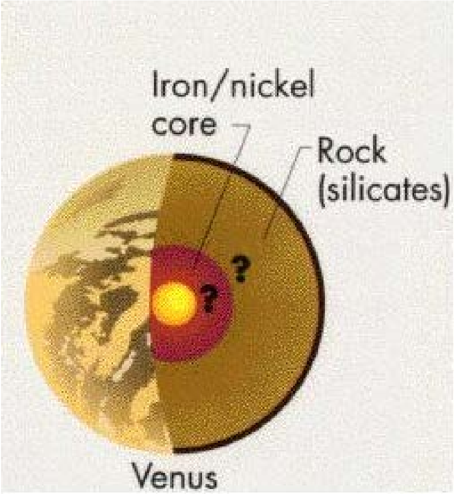
**Mercury** dynamo is probably weaker than Earth's because it is driven by thermo-compositional convection associated with inner core solidification The outer region of the liquid core is stably stratified with the dynamo operating only at depth, where a strong field is generated.

Classical convection driven core dynamos have a hard time to reproduce the observations

*CRUSTAL MAGNETIC FIELDS*
Strong ancient rock magnetization (MESSENGER)



# VENUS    B=0

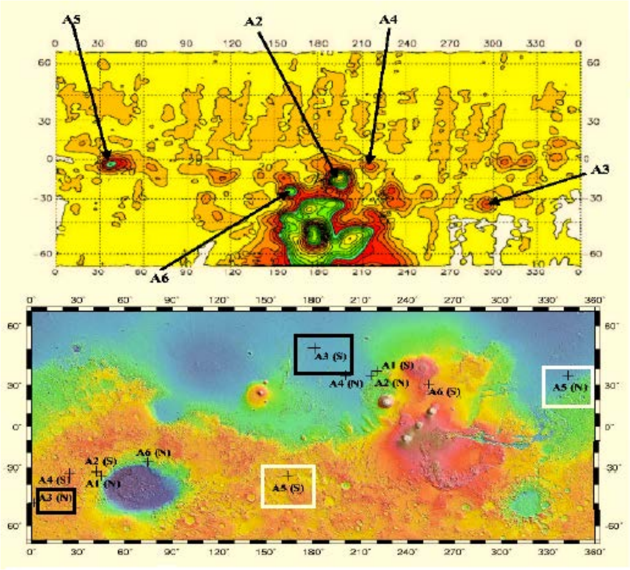



- **SLOW ROTATION**

**•Absence of solid nucleus or its too high temperature preventing crystallization of iron/nickel**

**•Presence of sulfur reducing the melting temperature**

# MARS



**Strong active dynamo existed 4 billions years ago**

**Decay due to planetary cooling**
**Insufficient heat flux to support dynamo**

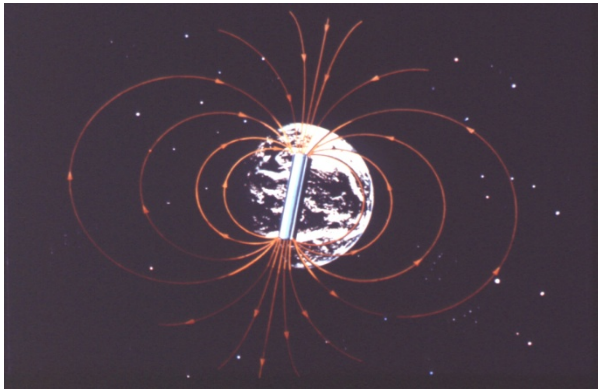
**Martian magnetic field inversions**

**inhomogeneous magneization of a crust**

# Earth's MAGNETIC FIELD and Field- aligned currents

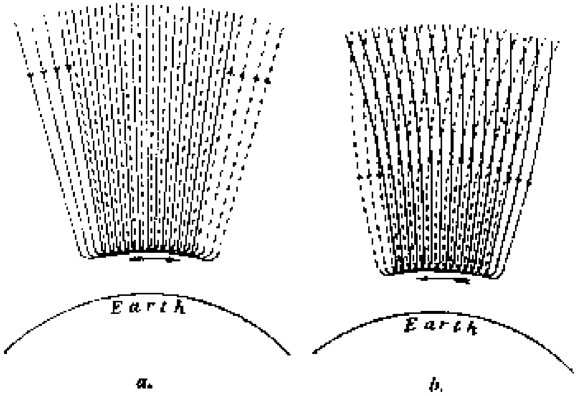
C. F. Gauss (1777-1855)

W. Weber (1804-1891)



**Observations of the Magnetic field and its variations**
**Magnetic society in Gottingen (1831)**

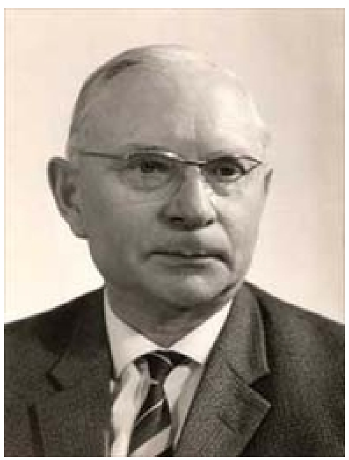

**1867-1917**




**BIRKELAND CURRENTS =PARALLEL CURRENTS**

# EARLY VISION OF SOLAR ERUPTIONS WITH THE EARTH

Sydney Chapman (1888-1970)



Julius Bartels (1899-1964)

## Chapman one of the pioneers of solar-terrestrial physics.

Chapman studied magnetic storms and aurorae, developing theories to explain their relation to the interaction of the Earth's magnetic field with the SW

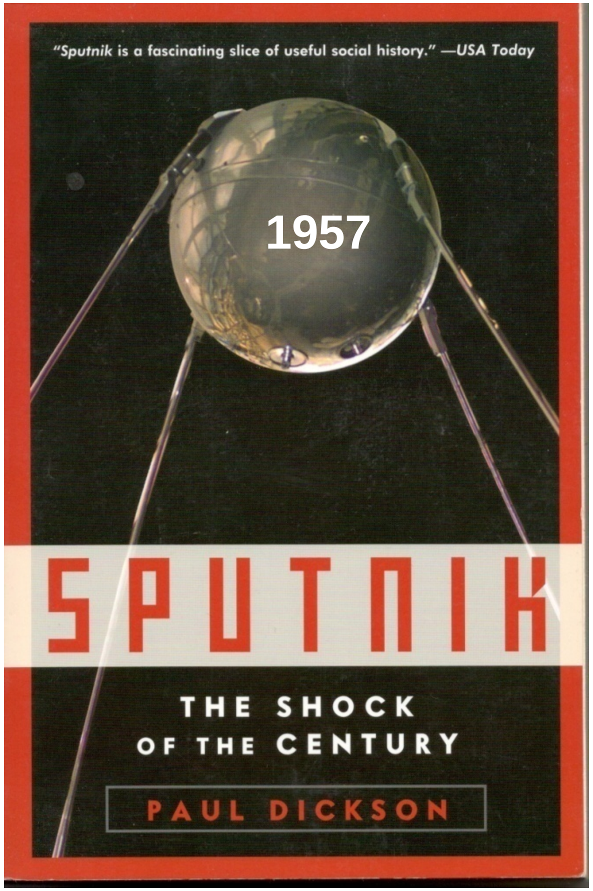
He disputed and ridiculed the work of Kristian Birkeland and Hannes Alfvén, later adopting Birkeland's theories as his own.

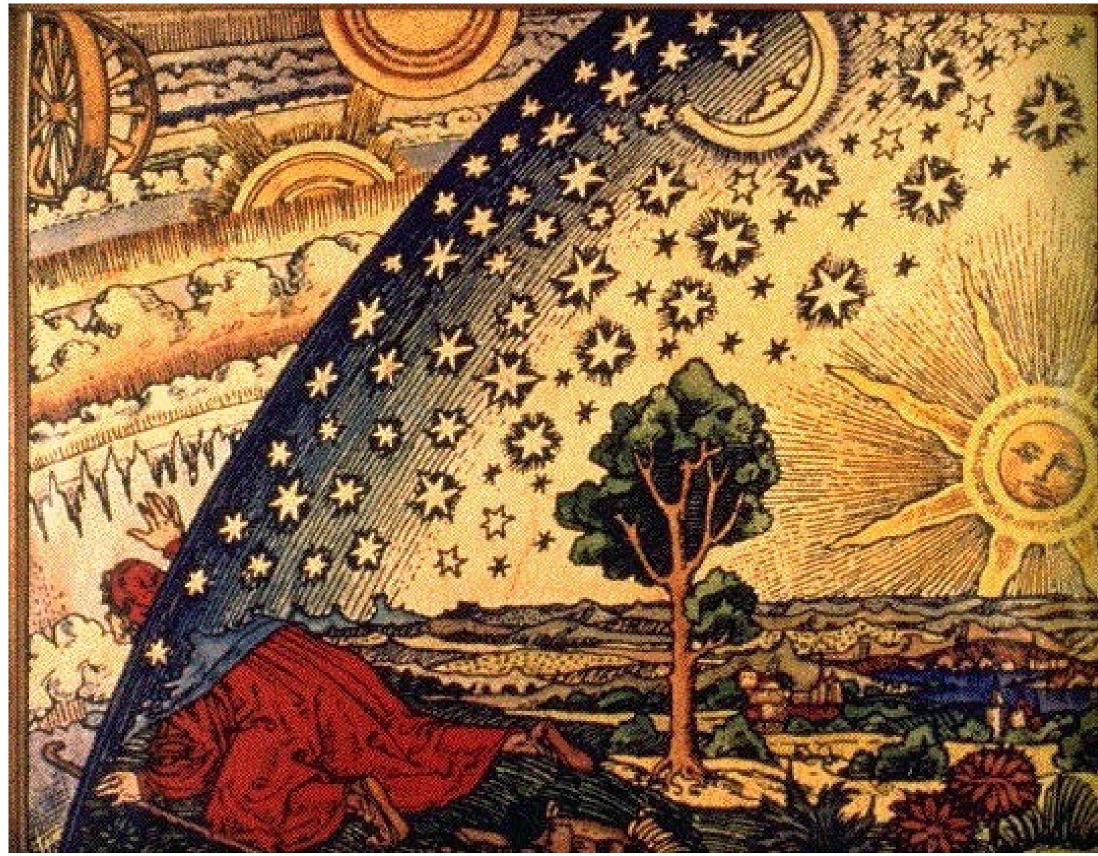
Chapman and his first graduate student, V. C. A. Ferraro, predicted the presence of the magnetosphere in the early 1930s

In 1940 Chapman and Julius Bartels published classical book in two volumes on geomagnetism. which was to become the standard text book for the next two decades[]

In 1946 Chapman coined the term: Aeronomy, for high-altitude research into atmosphere/space interaction.

# SPUTNIK OPENED TO SCIENTISTS “ ANOTHER SKY AND ANOTHER EARTH”



A medieval monk who pierces the top of the heavenly vault and sees a completely different world

– another sky and another Earth.

# EPOCH OF GREAT ”GEOGRAPHIC “ DISCOVERIES

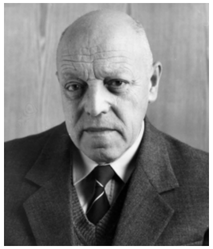
· **1959 Thomas Gold proposed the name "Magnetosphere”**

. **1957-1959 : VAN AllEN & VERNOV radiation belts**

**1959 Gringauz, Birman Solar wind**
**1960 Gringauz, Carpenter Plasmasphere**

· **1961 James Dungey: RECONNECTION -mechanism for transmitting solar wind energy to the magnetosphere is the direct magnetic linkage between the two.**

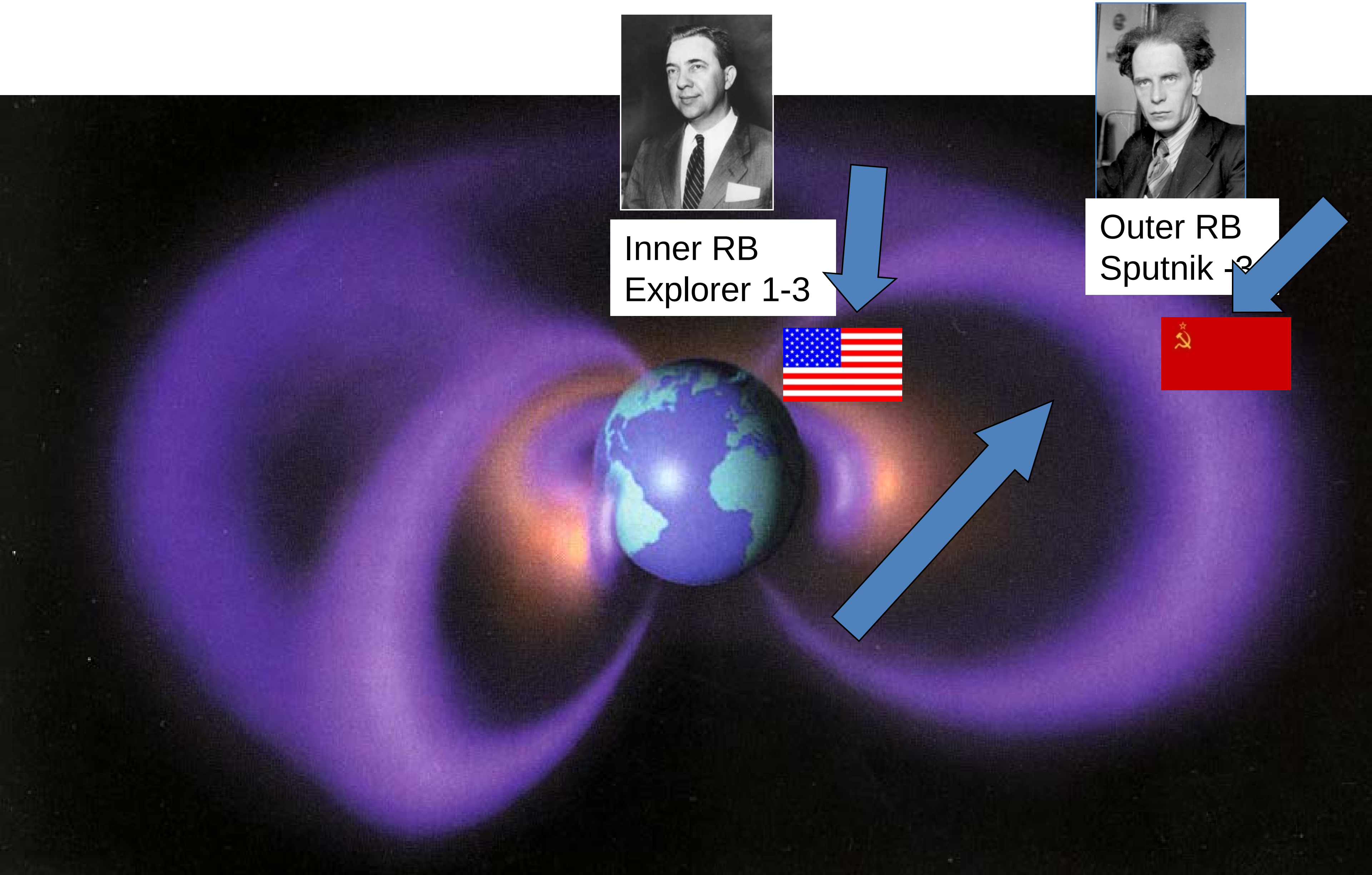
· **1964 IMP-1: a large bow shock formed in the solar wind ahead of the magnetosphere, and a long magnetic tail on the night side of the Earth.**



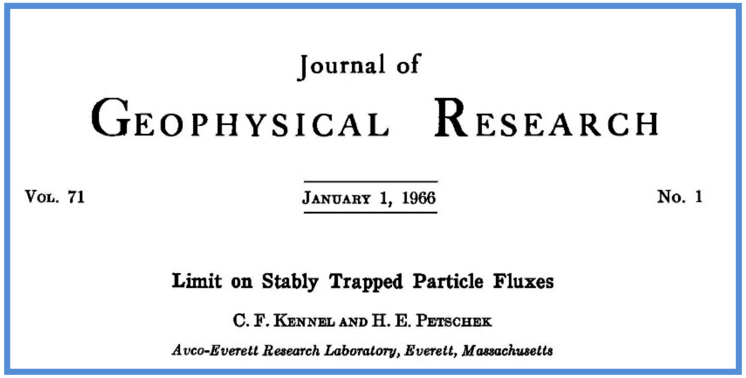
· **1965. Norman F. Ness The magnetotail is discovered: ·**

**1983 ISEE-3 observes the distant tail plasma flows (past about 70 RE) away from Earth. This is later confirmed by the Geotail spacecraft.**

# DISCOVERY OF RADIATION BELTS (1958)



# Van Allen/Vernov Belts

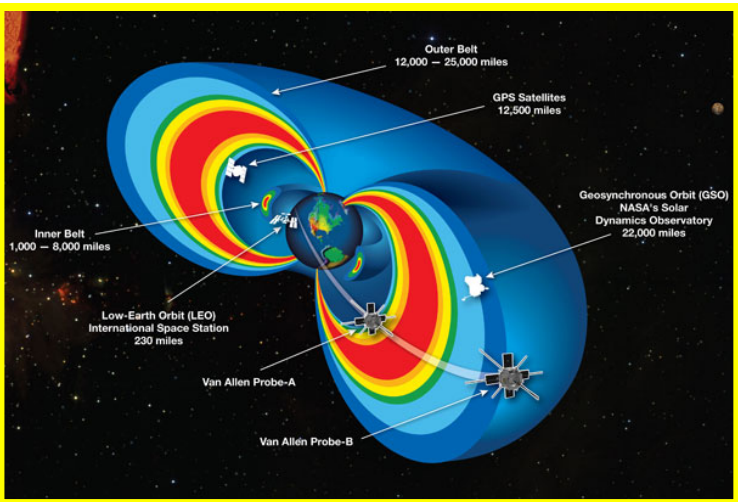

Journal of
GEOPHYSICAL RESEARCH

VOL. 71 | JANUARY 1, 1966 | No. 1

**Limit on Stably Trapped Particle Fluxes**

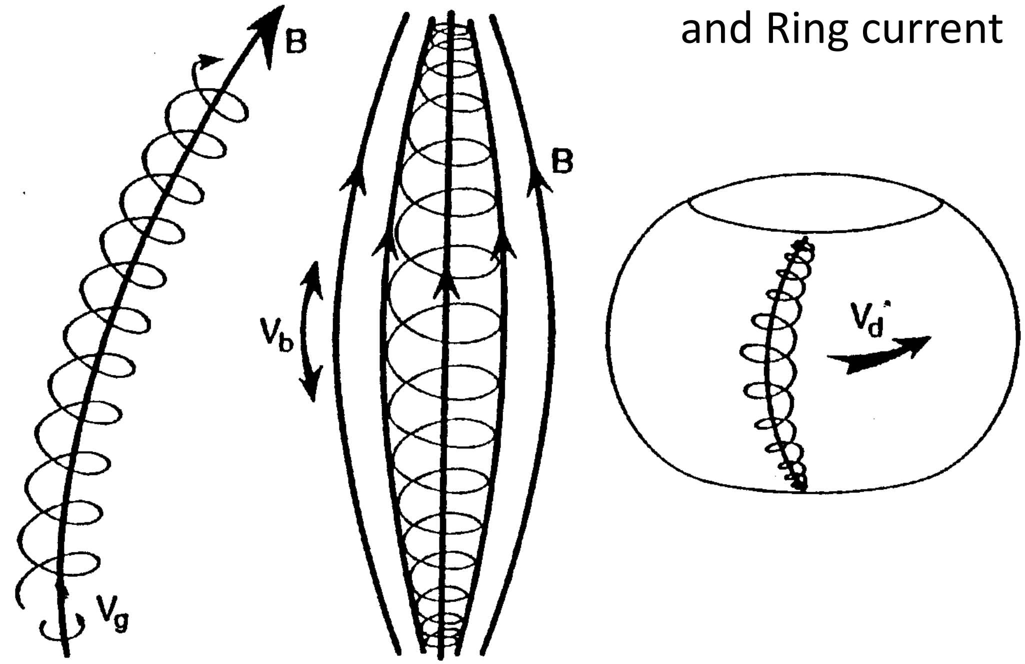
C. F. KENNEL AND H. E. PETSCHEK

*Avco-Everett Research Laboratory, Everett, Massachusetts*




**+ PRECIPITATION**
**Pitch- angle- diffusion**

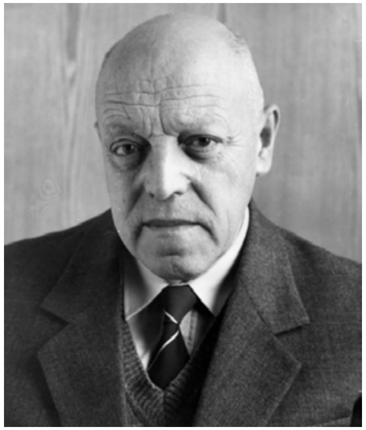
Magnetic F.L | Mirror point | Azimuthal drift and Ring current



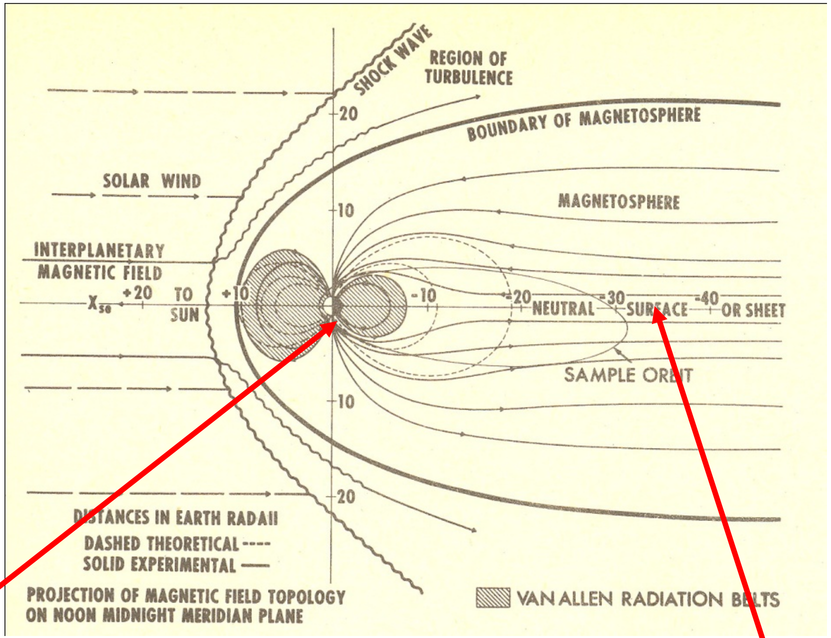

**Gyro-** | **Reflection** | **Drift-**

**Simplest Guiding center drift motion**

# *Near Earth space: from dipole to magnetosphere and heliosphere*

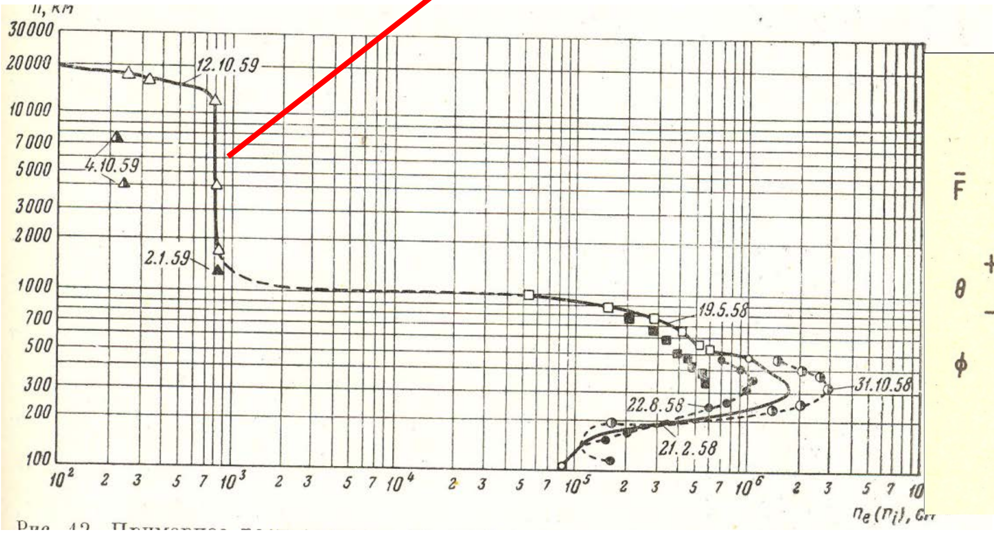


***K.I. Gringauz***
***Plasmasphere***

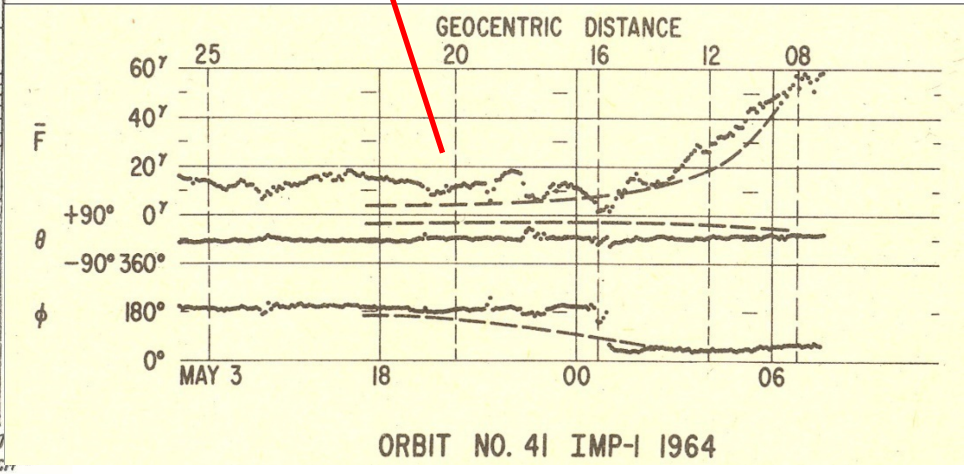



***N.Ness***
*Magnetotail*
*1965*

LUNA 1-2




Imp-1

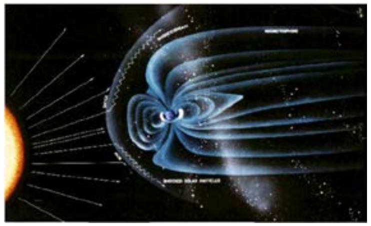


# WHAT WE HAVE LEARNED FROM THE MAGNETOSPHERE ?

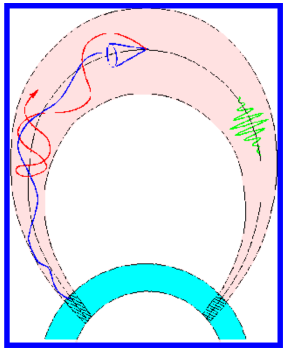
*Charles F. KENNEL*

SSB CHAIR

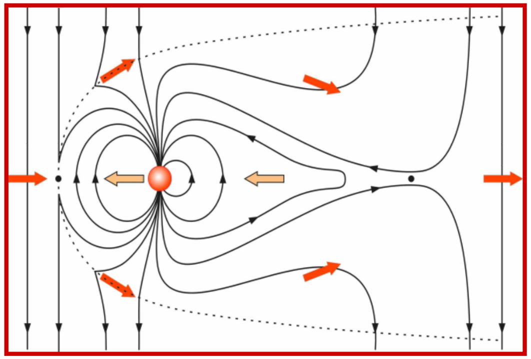
- COLLISIONLESS SHOCKS



- WAVE-PARTICLE INTERACTIONS
  IN RAD.BELTS & PLASMASPHERE



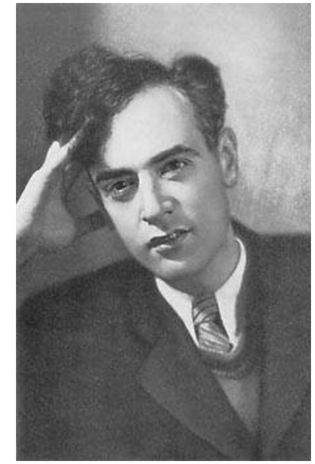
- RECONNECTION



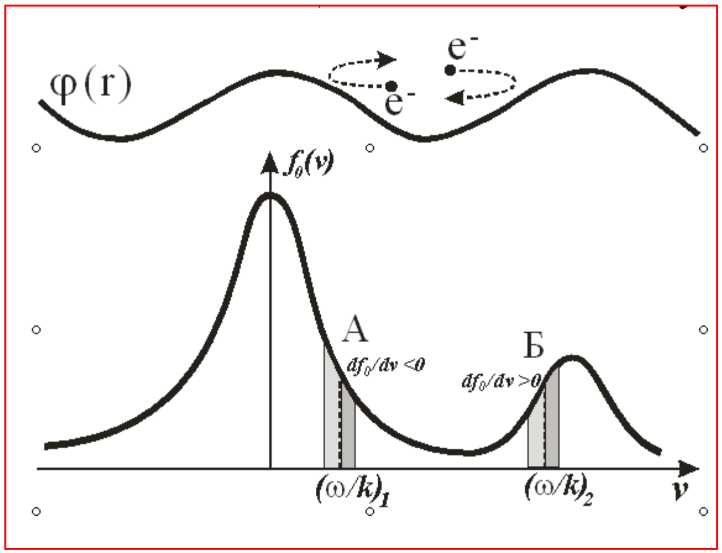
+ NONADIABATIC /CHAOTIC DYNAMICS OF CHARGED PARTICLES

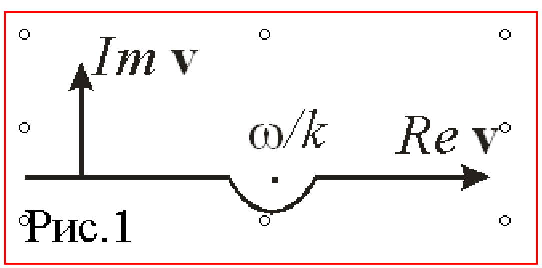
# COLLISIONLESS DISSIPATION

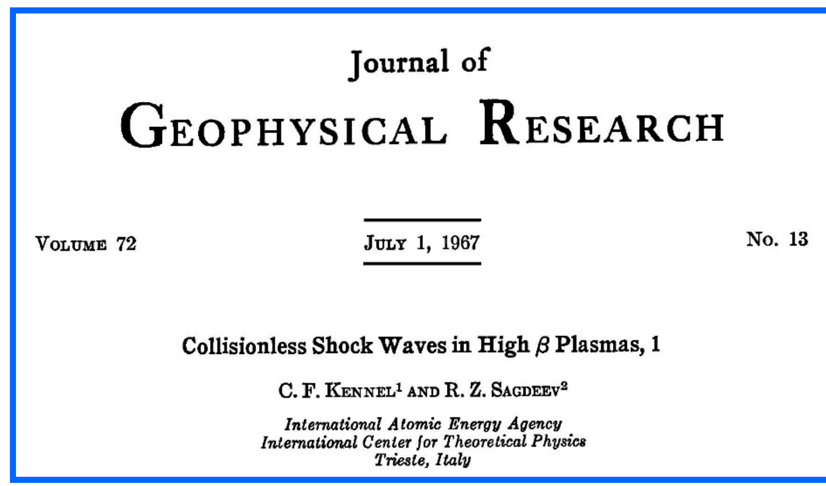
## *mean free path~ 1a.u.*



### LANDAU DAMPING (1946)



Journal of

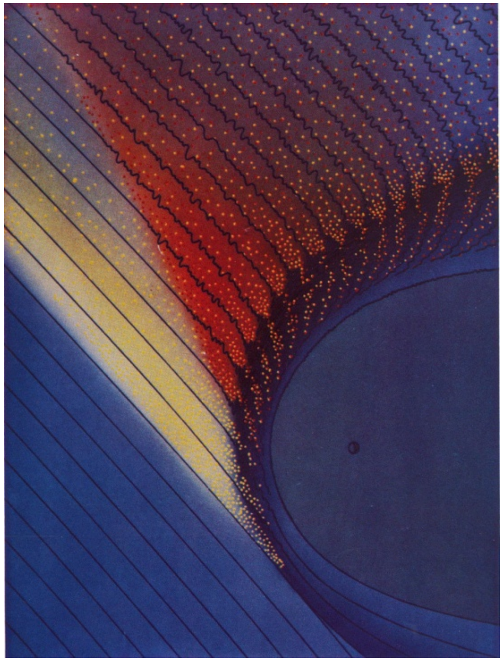
GEOPHYSICAL RESEARCH

VOLUME 72 | JULY 1, 1967 | NO. 13

**Collisionless Shock Waves in High $\beta$ Plasmas, 1**

C. F. KENNEL[1] AND R. Z. SAGDEEV[2]

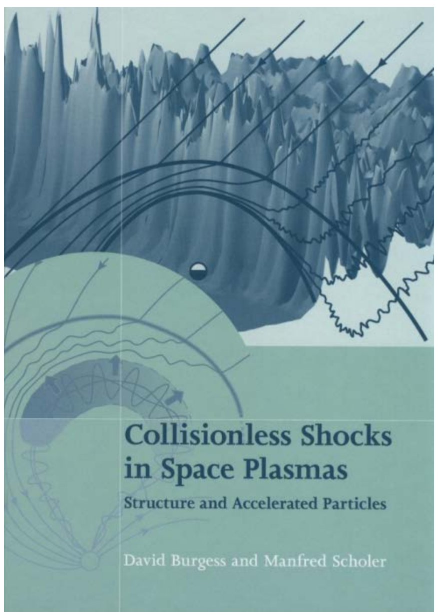
*International Atomic Energy Agency*
*International Center for Theoretical Physics*
*Trieste, Italy*

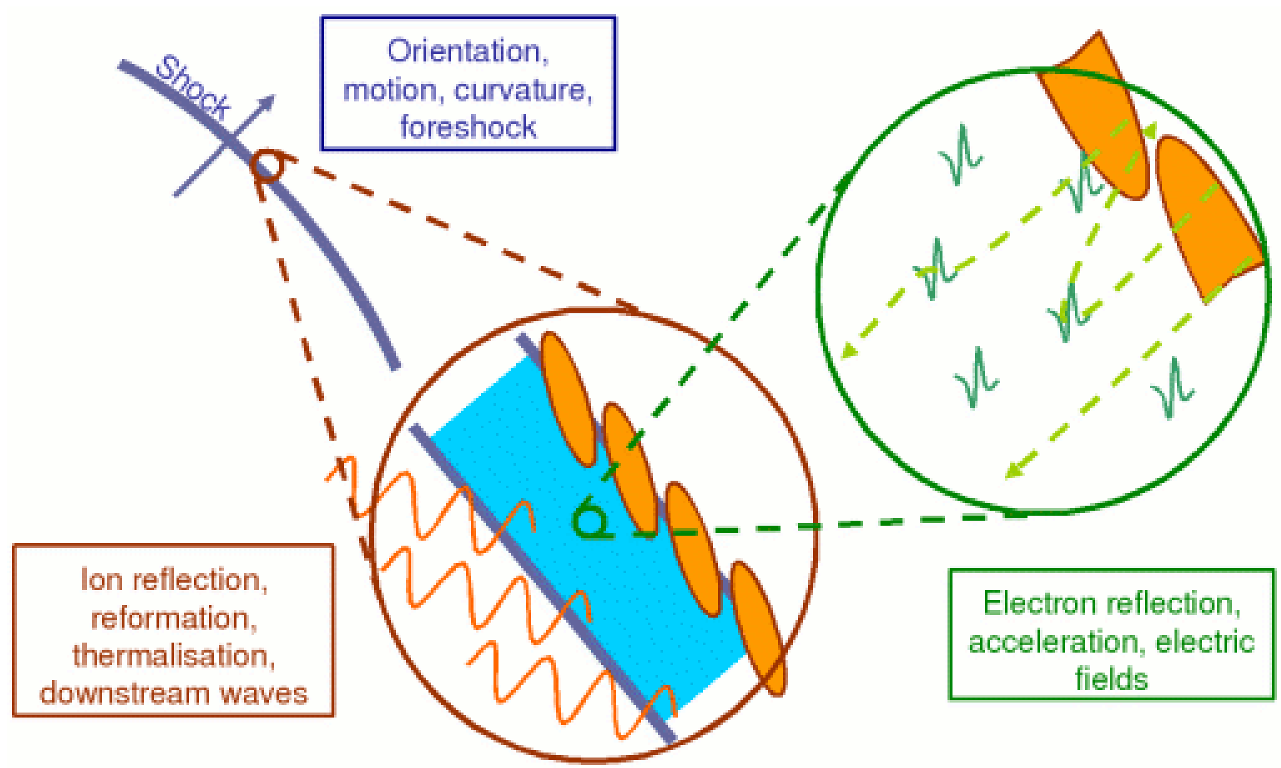


# COLLISIONLESS SHOCKS

**number of complicated nonlinear processes**

**ROALD SAGDEEV**

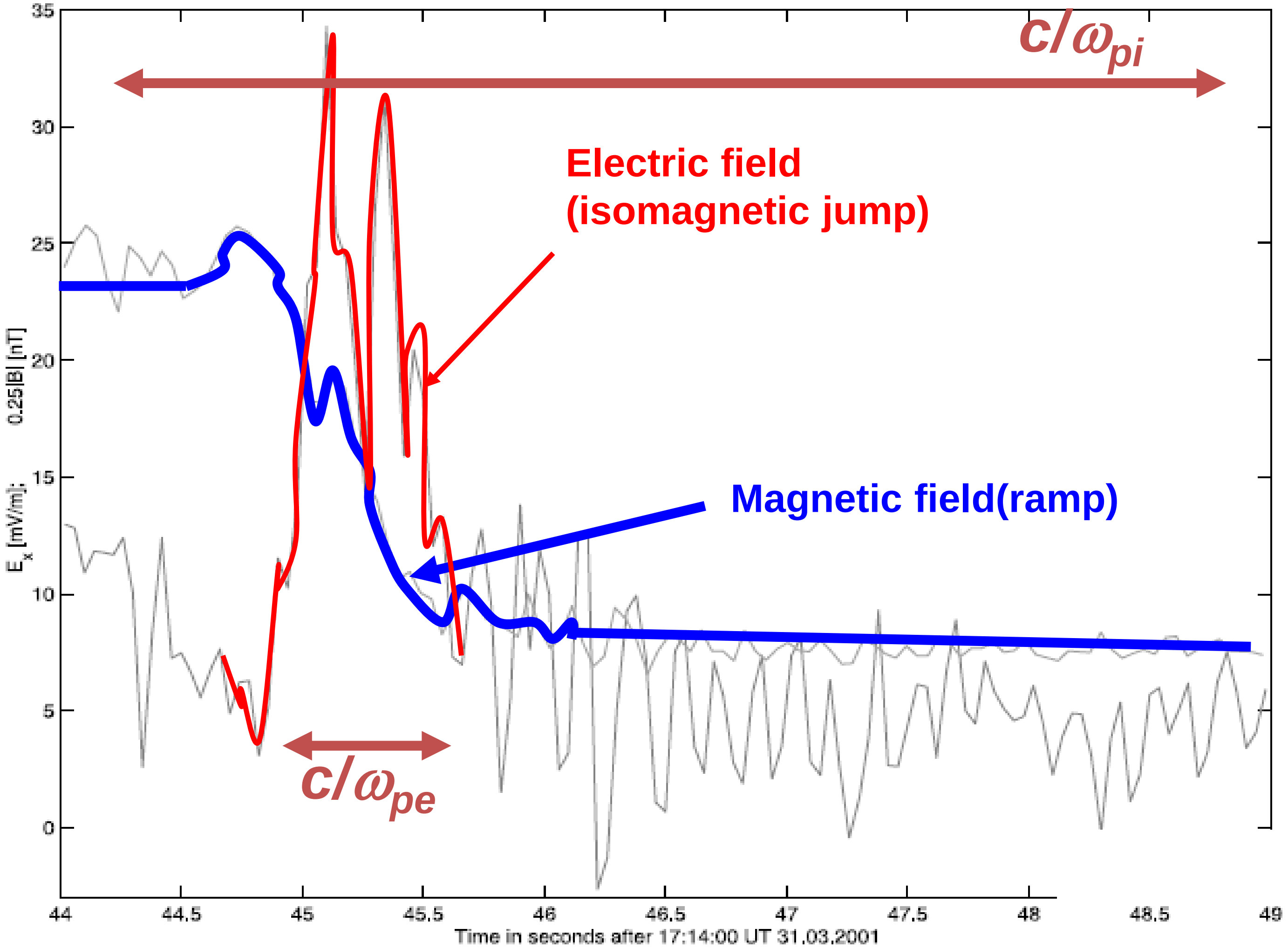


# Quasiperpendicular shock-most effective for SW braking

***Dissipation occurs at a narrow jump of electric field at ramp***

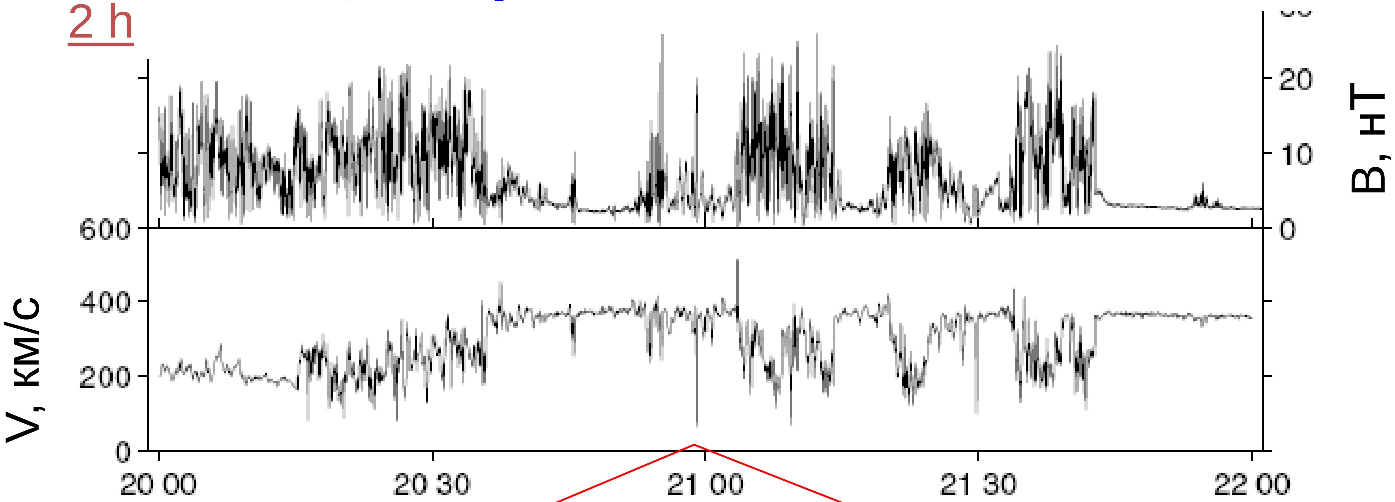
**(Nonlinear whistler wave )**



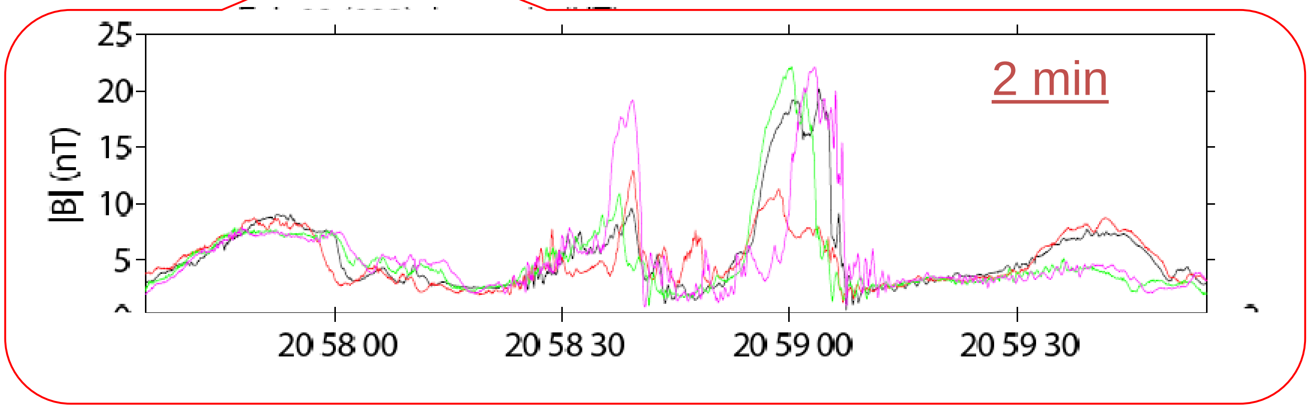

Theory *Galeev1988*

*Prognoz 8,10: VAISBERG . 1982, 1983*

# Quasiparallel shock wave




*Burgess et al 2005*

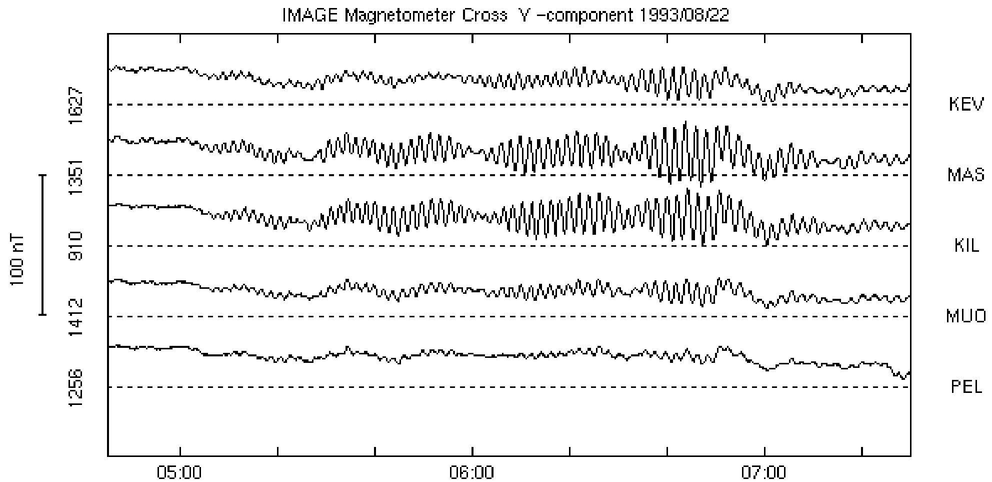


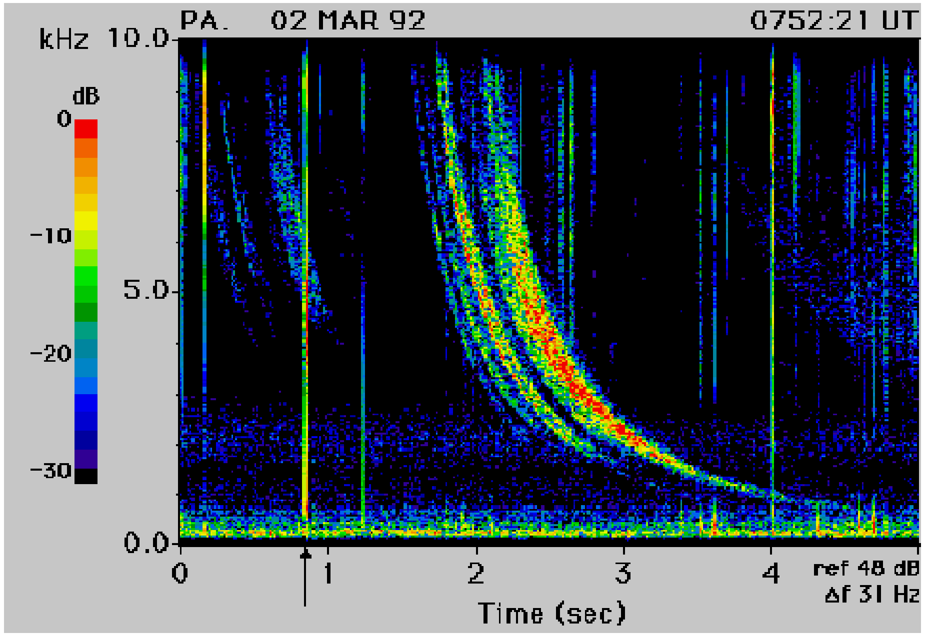

**Ions could move away from the shock front along B– diffuse structure >>c/$\omega_{pi}$**

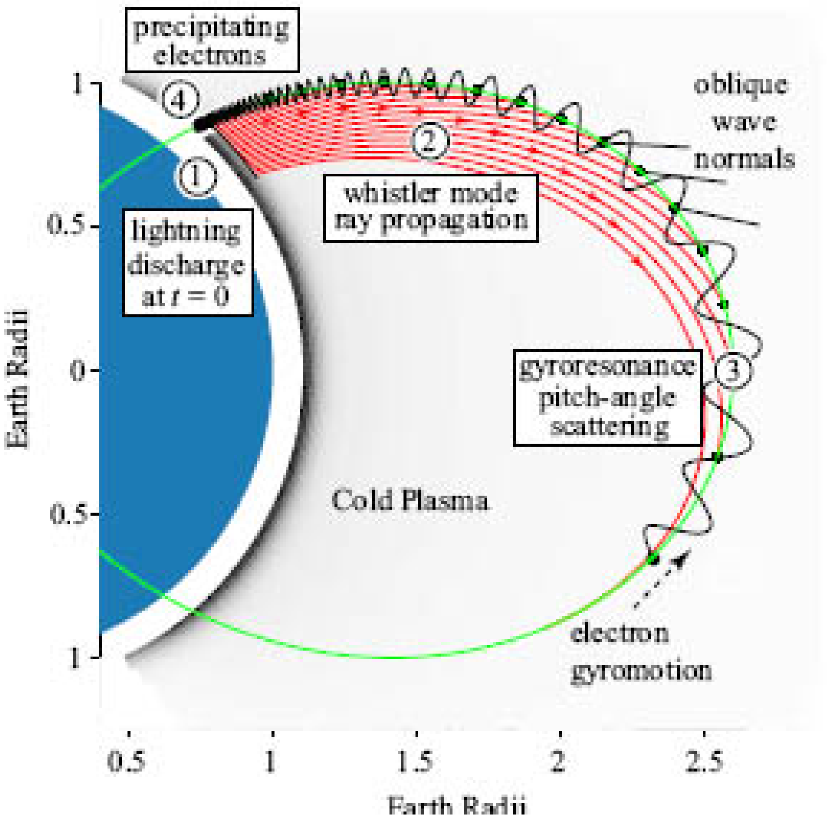
**Dissipation occurs at magnetic field substructures (shocklets)**

***(quasiperpendcular regime locally)***

# INTENSIVE WAVE_PARTICLE INTERACTIONS

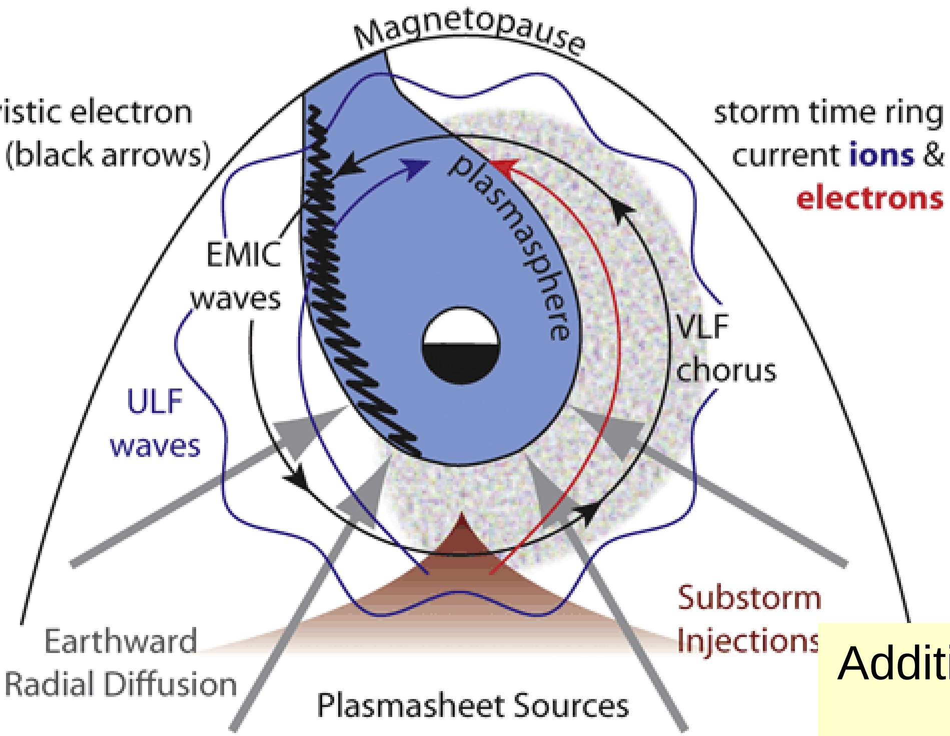


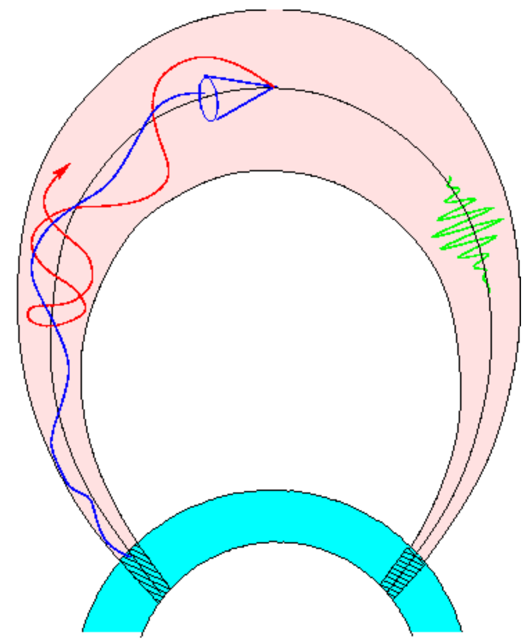



# ACCELERATION OF RELATIVISTIC ELECTRONS (few MEV)
# HOT_COLD PLASMA INTERACTIONS

## COLD PLASMASPHRERIC ELECTRONS SUPPORT BACKGROUND DISSIPATION



Additional acceleration by whistler waves generated by hot electrons

100 KeV electrons are injected from the tail

# WAVE PARTICLE INTERACTIONS

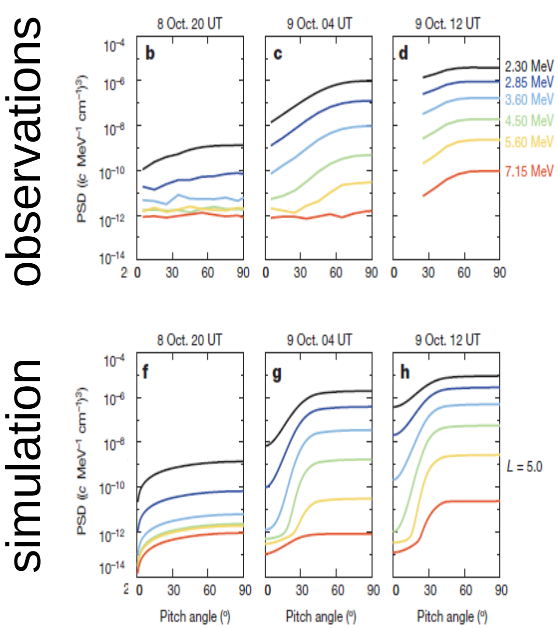
## Quazilinear diffusion of electrons by broad-band low amplitude waves with random phases

*FOKKER_ PLANCK EQUATION*

$$\frac{\partial f}{\partial t}=\frac{1}{G}\frac{\partial}{\partial\alpha_{\mathrm{eq}}}G\left(\left\langle D_{\alpha_{\mathrm{eq}}\alpha_{\mathrm{eq}}}\right\rangle\frac{\partial f}{\partial\alpha_{\mathrm{eq}}}+p\left\langle D_{\alpha_{\mathrm{eq}}p}\right\rangle\frac{\partial f}{\partial p}\right)$$
$$+\frac{1}{G}\frac{\partial}{\partial p}G\left(p\left\langle D_{\alpha_{\mathrm{eq}}p}\right\rangle\frac{\partial f}{\partial\alpha_{\mathrm{eq}}}+p^{2}\left\langle D_{pp}\right\rangle\frac{\partial f}{\partial p}\right)$$

Vedenov, Velikhov, Sagdeev 1962
Kennel & Petschek 1964,
Andronov & Trakhtengerts 1964
Explains radiation belt phenomena.

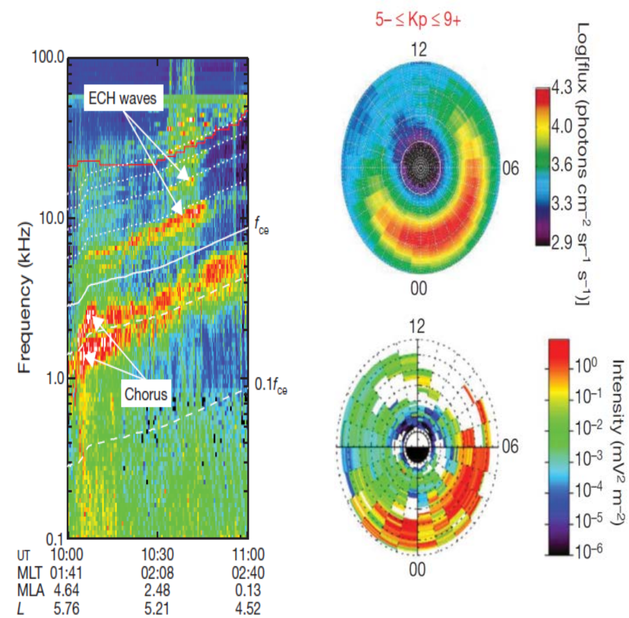
*Thorne et al. 2013 Nature*




**Acceleration** of electrons by chorus whistler waves to several MeV

**Scattering and precipitation** of 0.1-10 keV electrons **to duffise aurora** by whistler and electron-cyclotron waves.

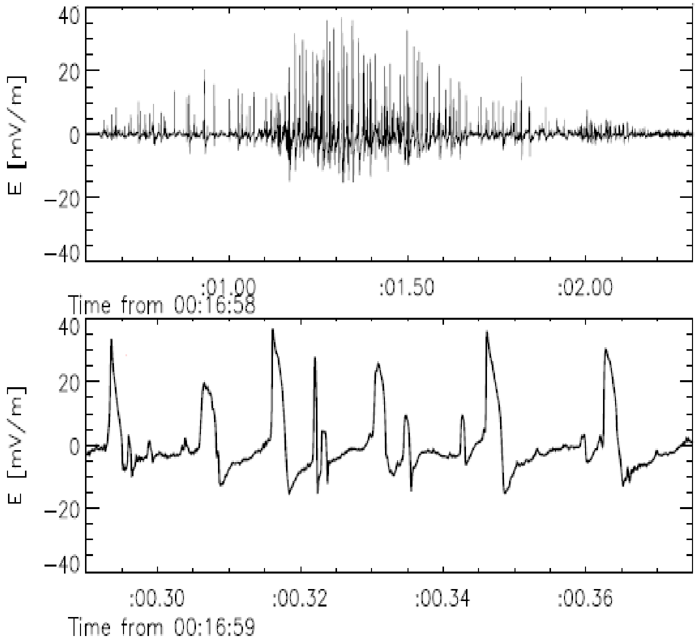
*Thorne et al. 2010 Nature*



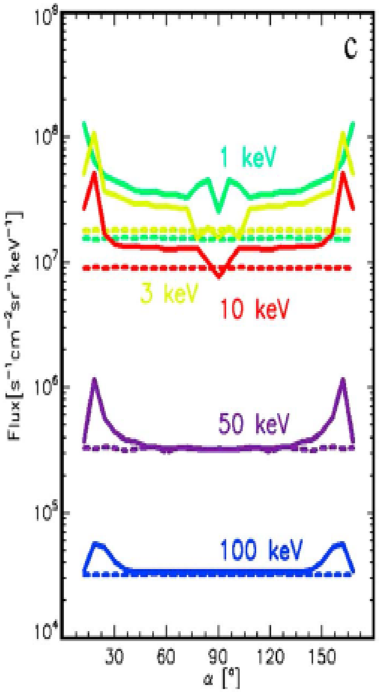
# Nonlinear electrostatic turbulence
# (time domain structures) in radiation belts

**Parallel E-field bursts 10-100 mV/m**

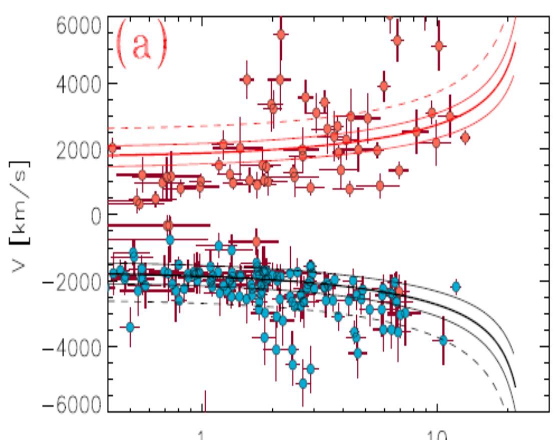
(Mozer et al. 2013, 2014 PRL)




Resonant interaction with electrons results in parallel beams with 1-100 keV (Mozer et al. 2016 GRL)

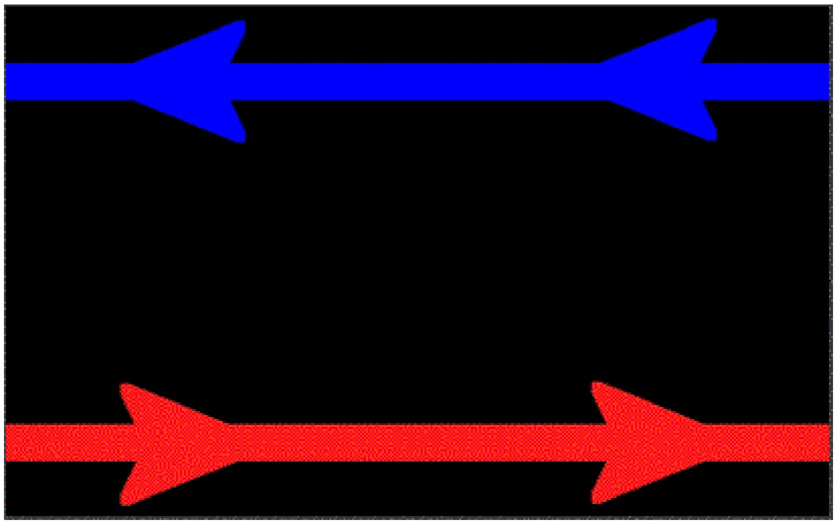


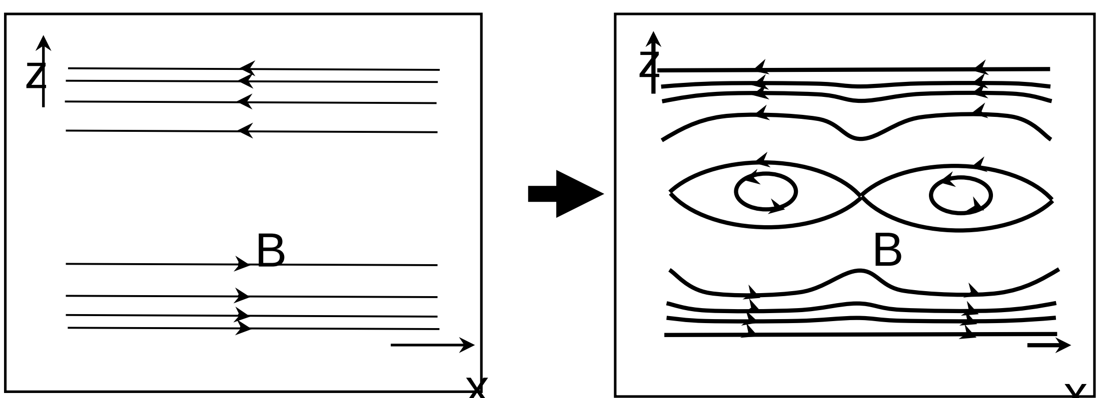

Dispersion relation corresponds to electron-acoustic solitons (Vasko et al. 2017 GRL)




**New type of wave activity creates seed electrons for MeV acceleration**

# RECONNECTION
# IN HIGH TEMPERATURE PLASMA






**FORCED RECONNECTION**
**versus**
**SPONTANEOUS RECONNECTION**

**MAGNETIC FIELD IS FROZEN INTO ELECTRON COMPONENT OF PLASMA**

**RESISTIVITY IS REQUIRED !**

**COLLISIONAL**
**or**
**COLLISIONLESS**

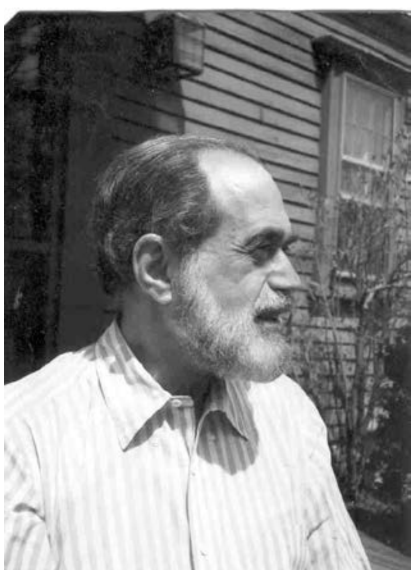
# Spontaneous tearing & reconnection?

On Frozen-In Field Lines and Field-Line Reconnection

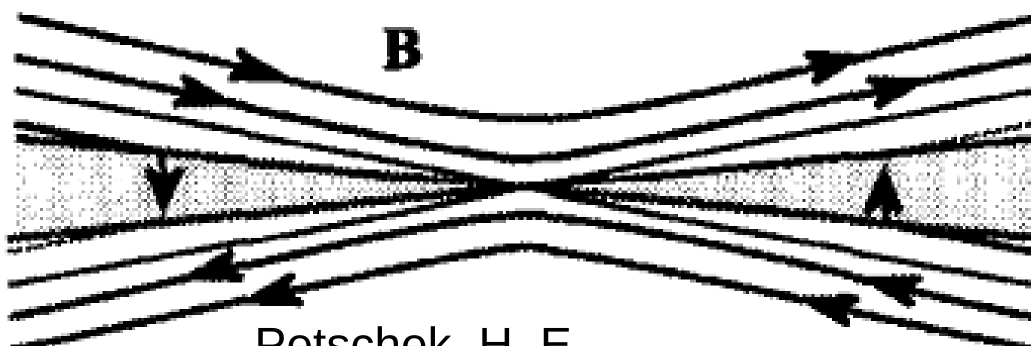
Hannes Alfvén JGR, 1976

It is shown that "frozen-in magnetic field lines" and "magnetic field-line reconnection" are unnecessary and often misleading concepts

Hannes Alfven

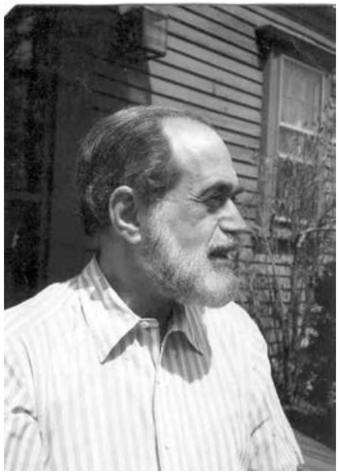


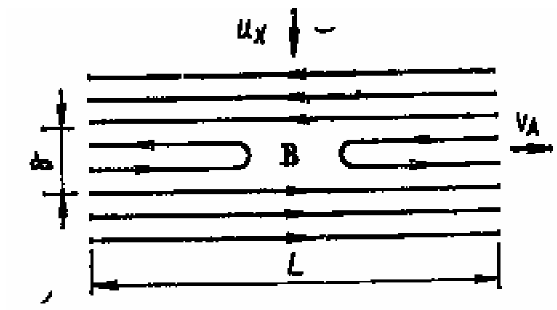
Harry Petschek



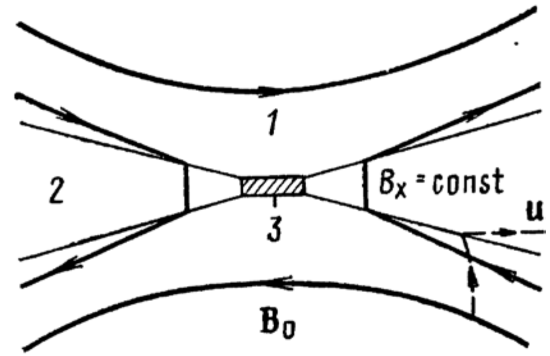

Petschek, H. E.
Magnetic field annihilation
NASA Spec. Pub., 1964.

# STEADY STATE PLASMA FLOW WITH RECONNECTIO



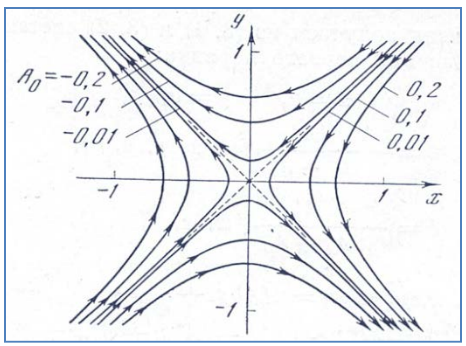



Sweet-Parker model

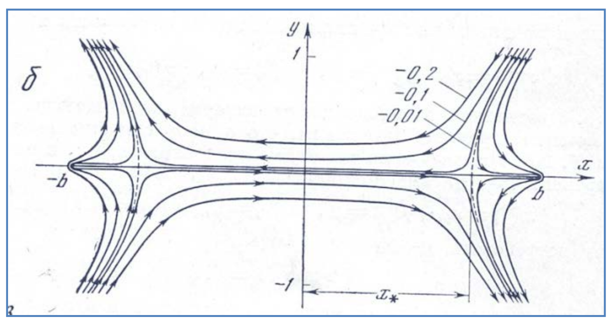



Petschek model

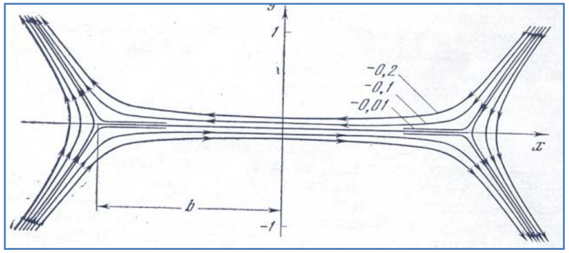
Petschek, H. E.
Magnetic field annihilation
NASA Spec. Pub., 1964.

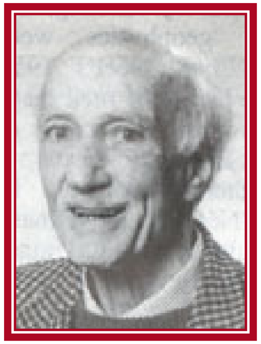



Dynamic thin current sheet



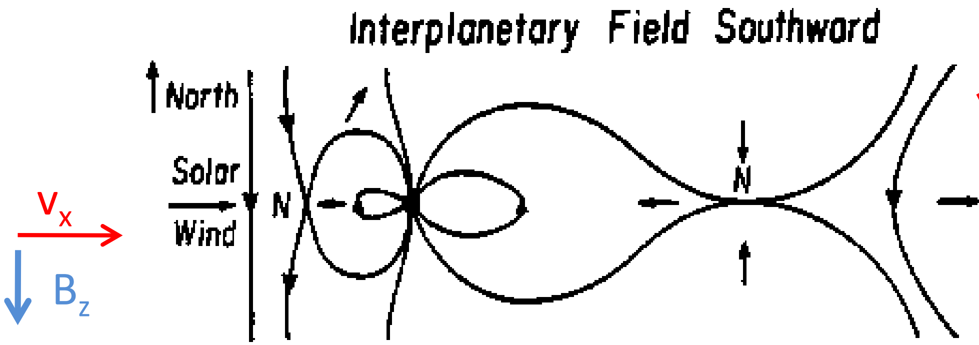

S.I.Syrovatsky

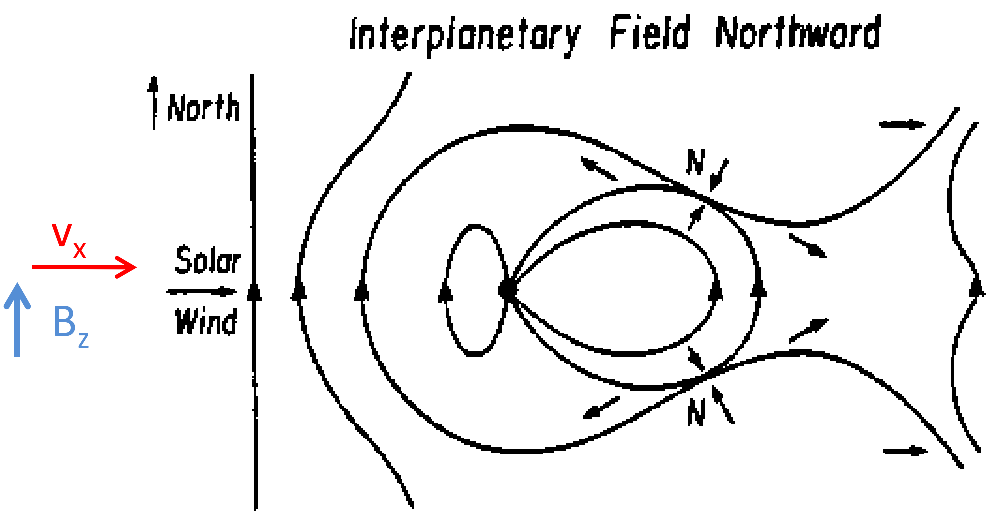




# RECONNECTION PARADIGM

### *DUNGEY MODEL*



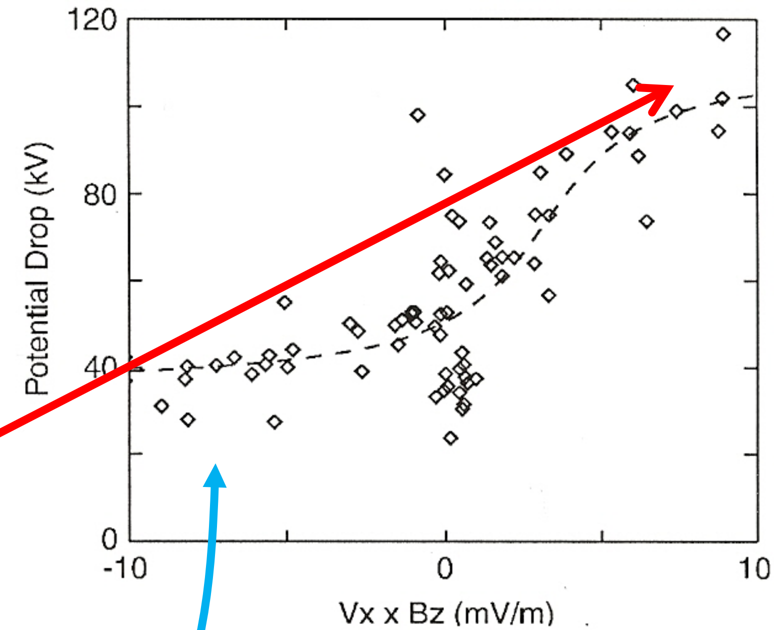



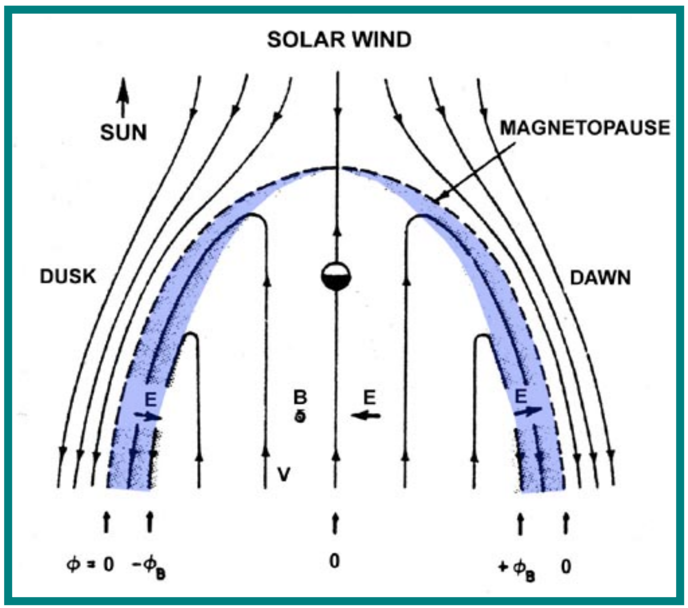

Fig. 5. An arctangent fit to $\Phi_{PC}$ as a function of $E_{SW}$. (Reprinted from Russell et al. (2001), Fig. 8 lower panel, with permission from the American Geophysical Union.)

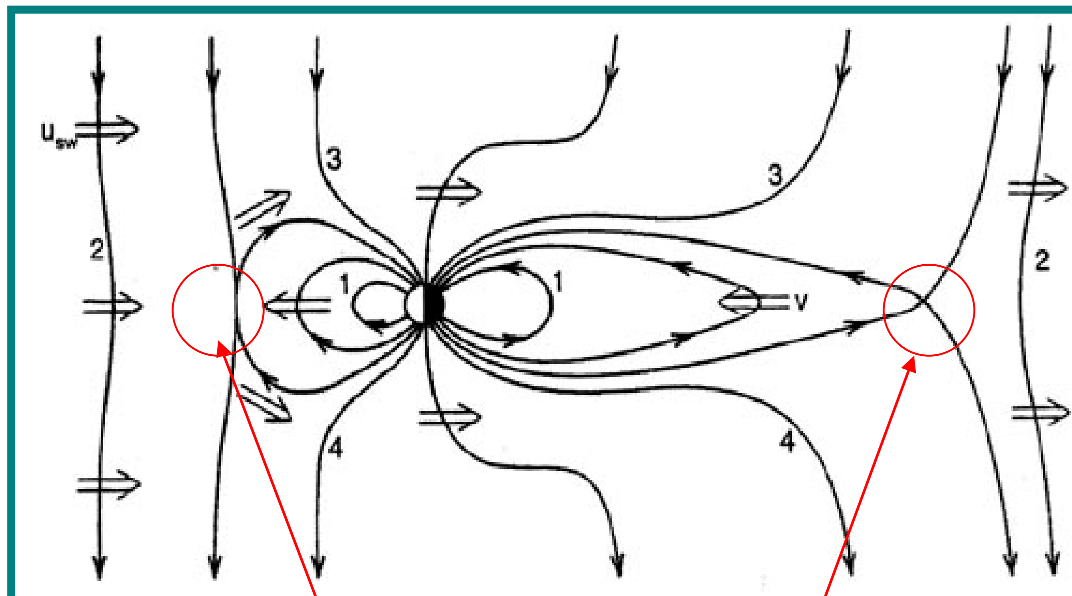
**+Quasiviscous drag via flanks**
**Mechanisms ?? TBC**

**GLOBAL RECONNECTION MODEL EXPLAINS THE LARGE STRUCTURE OF MAGNETOTAIL FAIRLY WELL**

# MAGNETOSPHERIC TOPOLOGY : CLOSED OR OPEN?

Axford & Hines vs Dungey

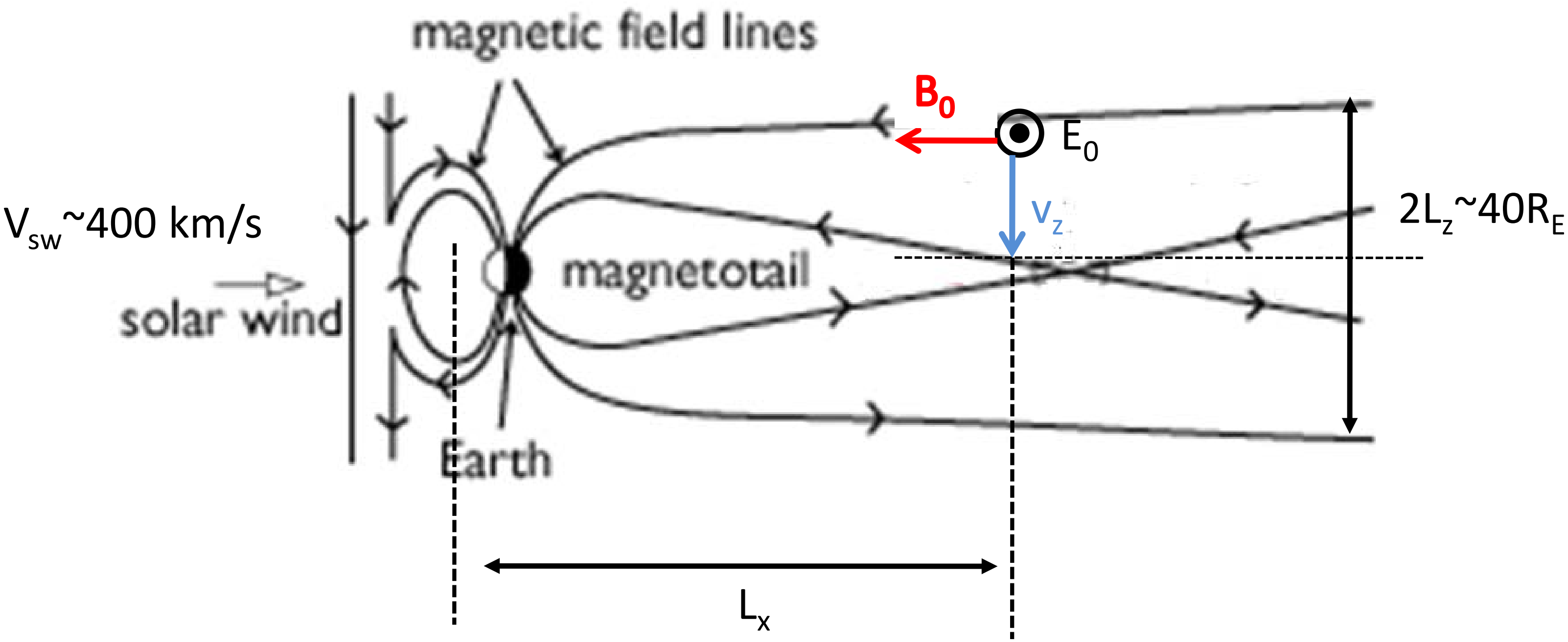



**Viscous interaction**

**Magnetic field lines reconnection**

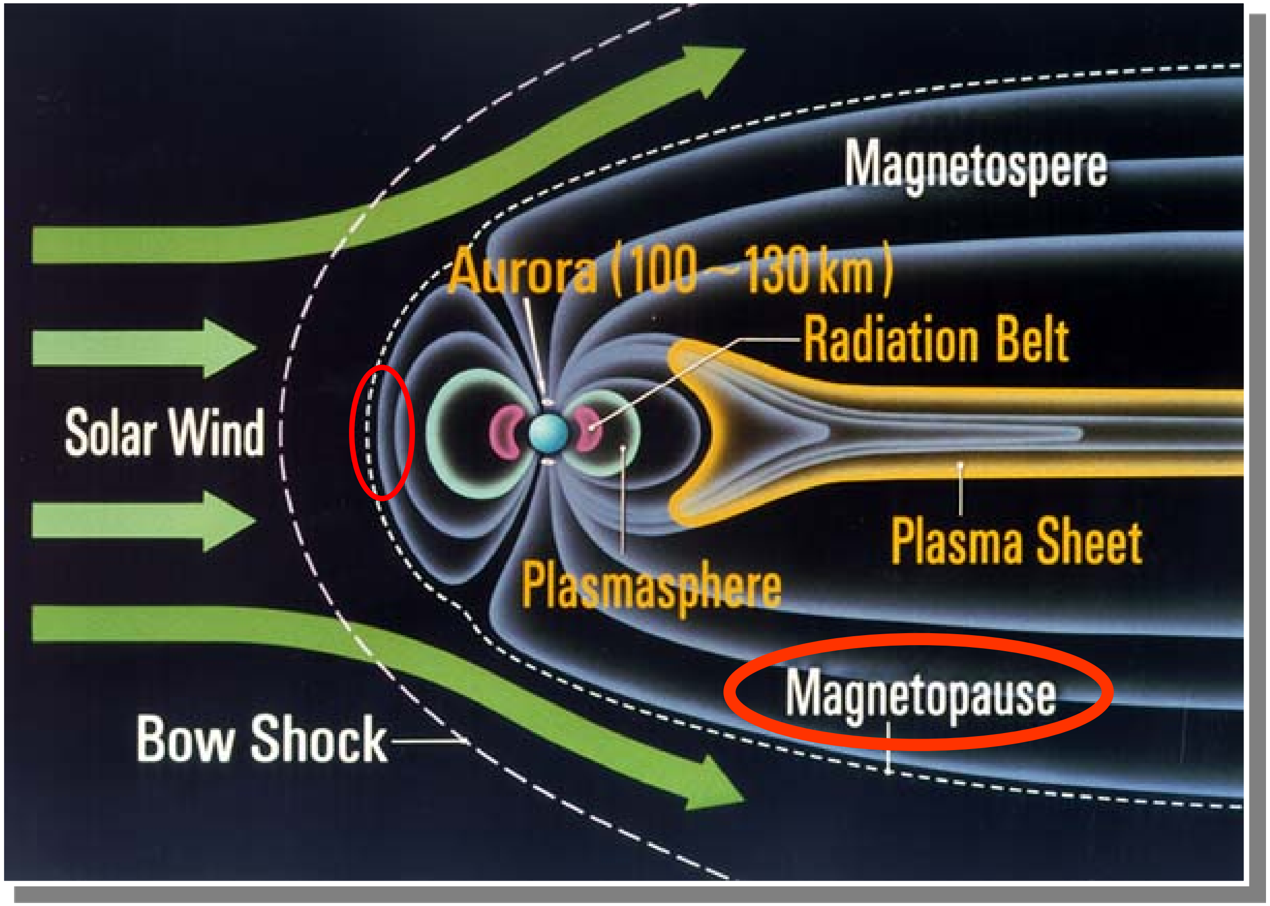
# LARGE SCALE SRUCTURE OF MAGNETIC FIELD




$$\frac{L_x}{L_z} = \frac{v_{sw}}{v_z} = \frac{v_{sw}}{c}\frac{B_0}{E_0} \sim 10-15$$ ➡ $L_x \sim 200\ R_E$ -300Re **VERY LONG TAIL**

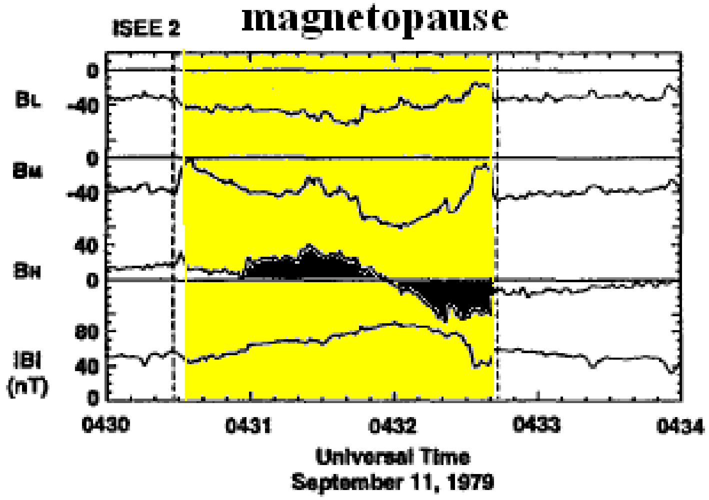
**GLOBAL RECONNECTION MODEL EXPLAINS THE LARGE STRUCTURE OF MAGNETOTAIL FAIRLY WELL**

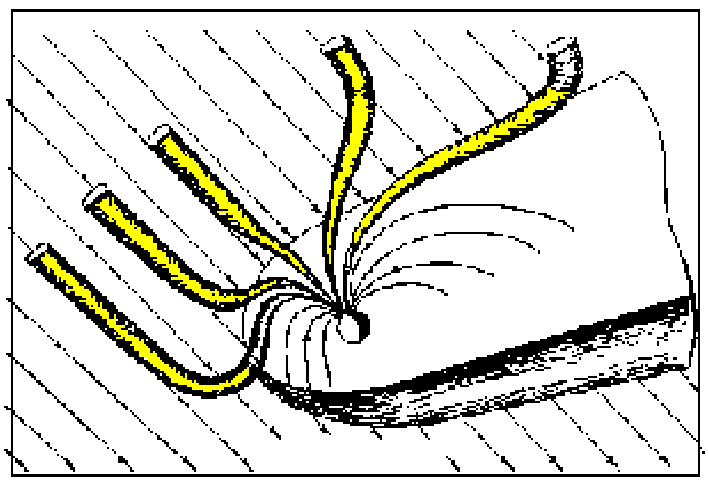
# Magnetospheric boundary: Magnetopause




**Transport of plasma across the boundary has been and is still a big issue**

**Flux transfer event at the Earth's magnetopause**



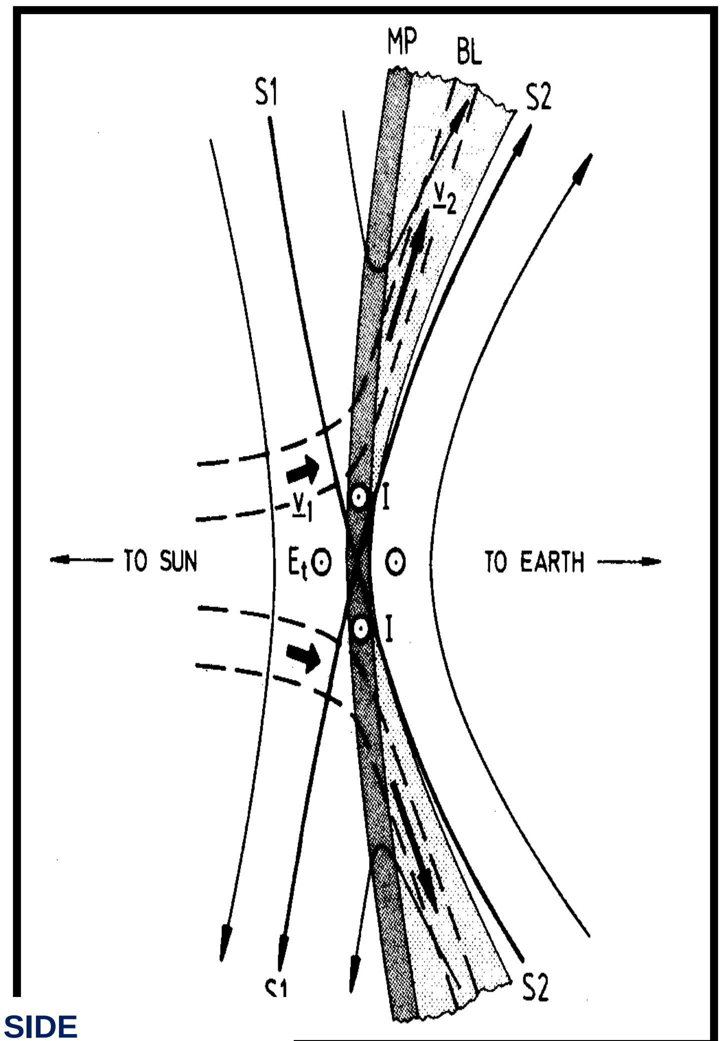



# FLUX TRANSFER EVENTS

***C.T. RUSSELL & WALKER***

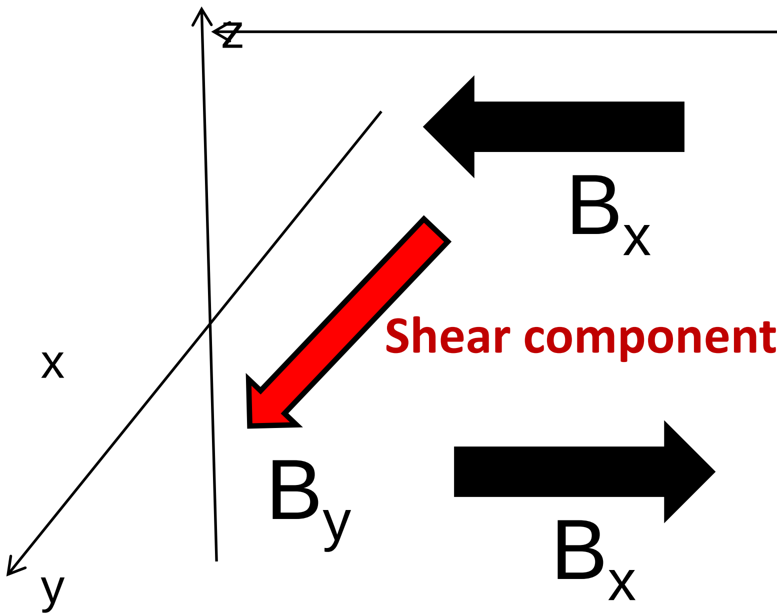
## FLUX TUBE RECONNECTION AT THE DAYSIDE MAGNETOPAUSE

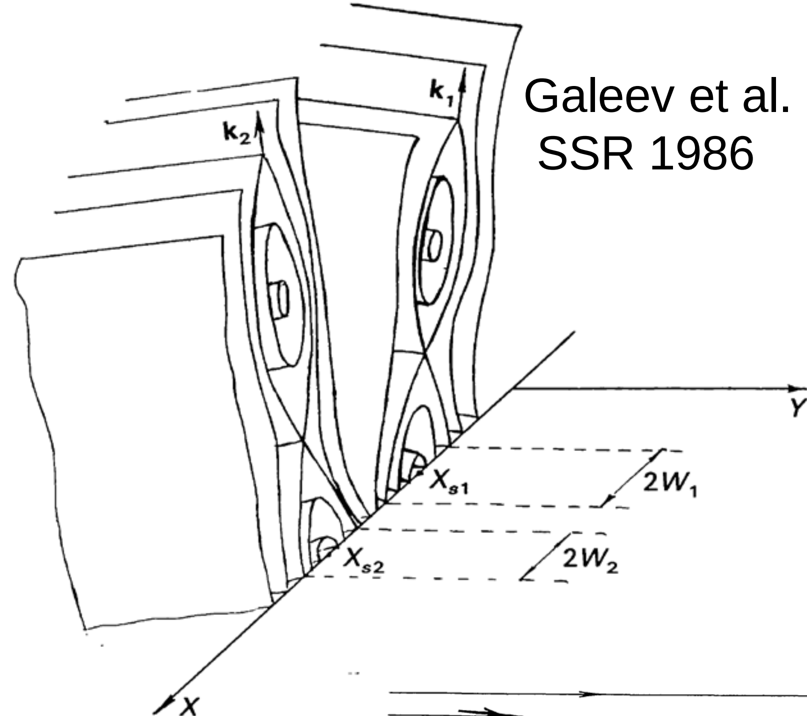
OFTEN "PATCHY" RECONNECTION



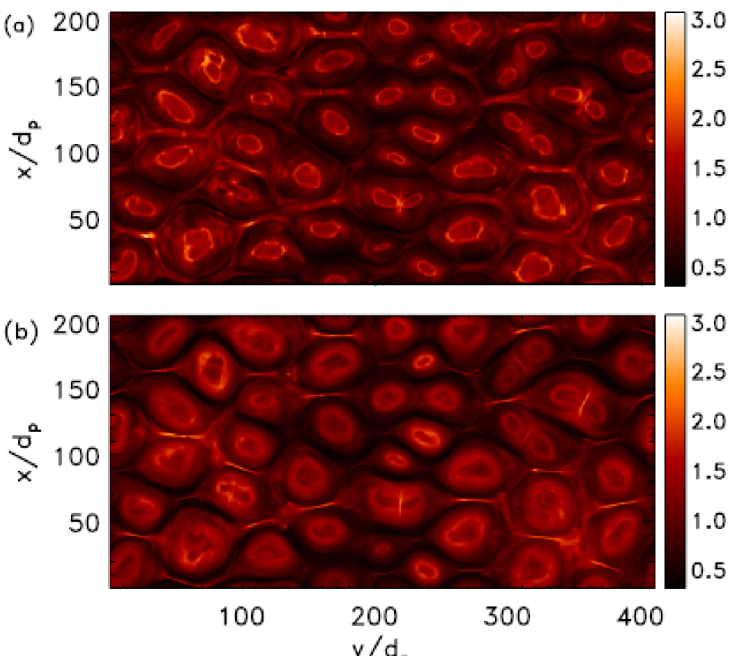

**CONVECTION OF RECONNECTED FLUX TUBES TO THE NIGHT SIDE**

# STOCHASIC DIFFUSION THROUGH MGP



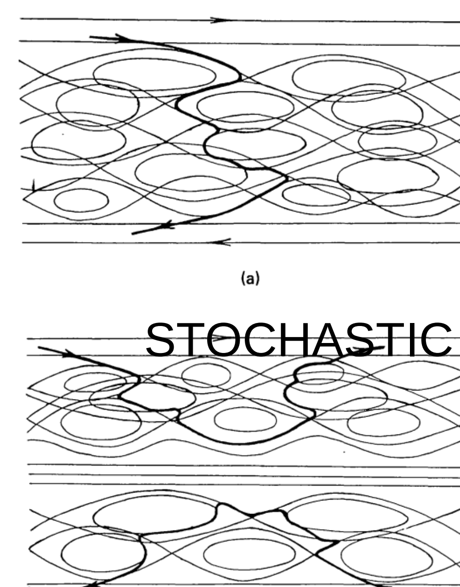

Galeev et al.
SSR 1986




z

$$\mathbf{B} = \mathbf{e}_x B_0 \tan(z/L) + \mathbf{e}_y B_y$$

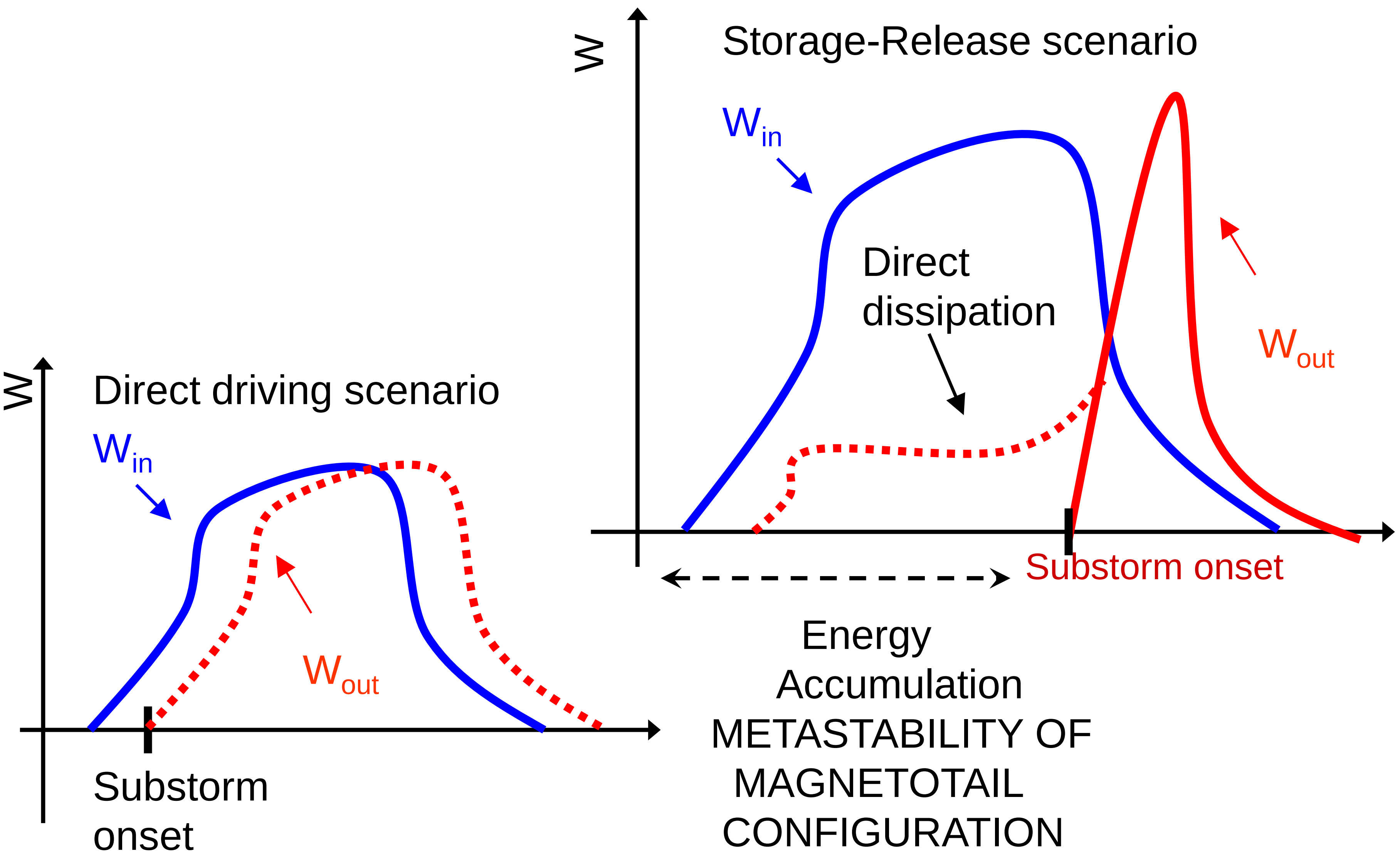
$$\mathbf{j} = \mathbf{e}_y \frac{cB_0}{4\pi L} \cosh^{-1}(z/L)$$




STOCHASTIC B

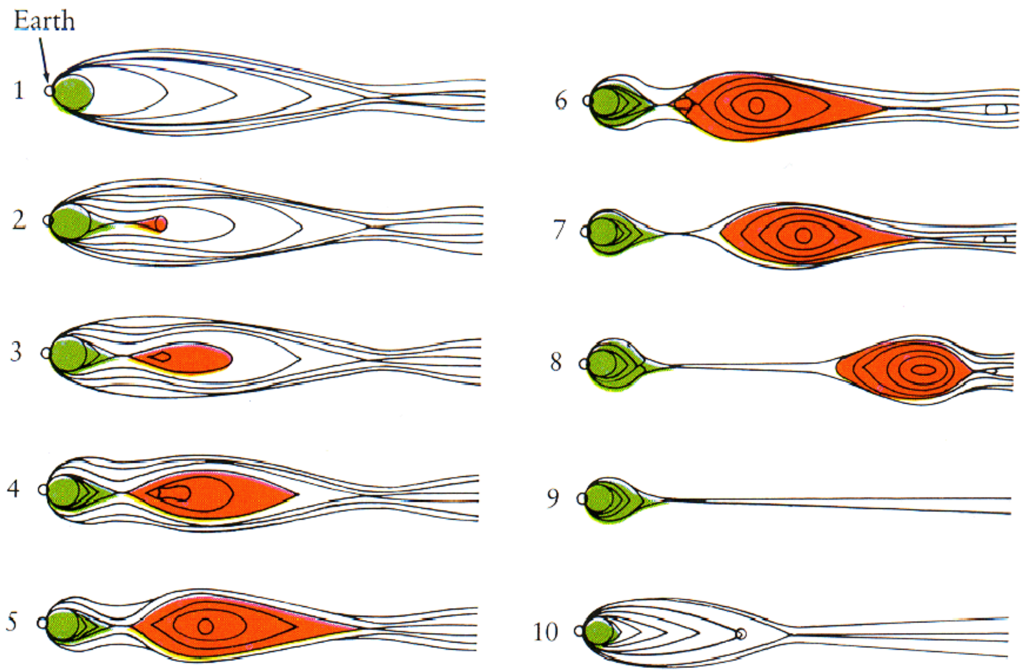
Drake et al.
2006, 2010

# Two scenarios of magnetospheric activity



# MAGNETOSPERIC SUBSTORMS

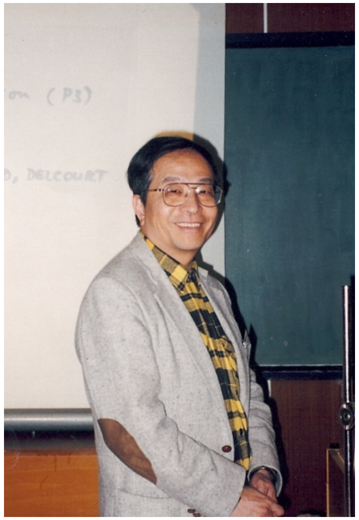
GROWTH PHASE
ONSET
EXPANSION PHASE
RECOVERY PHASE



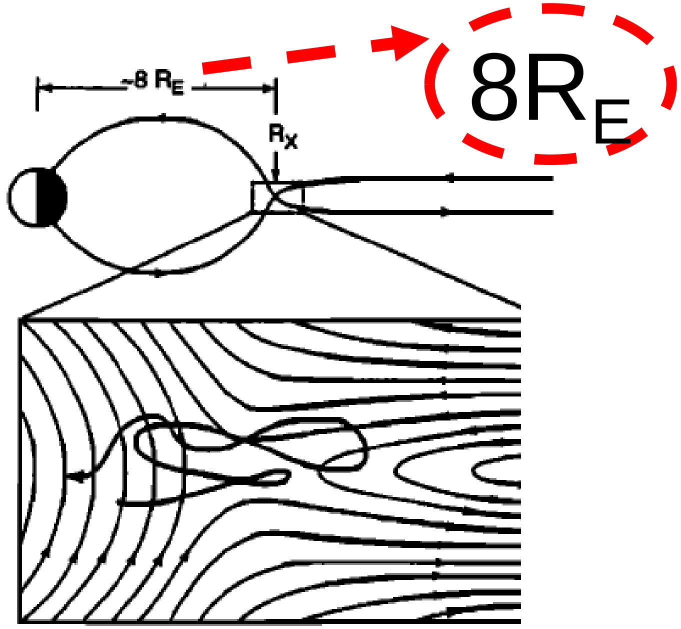

**FORMATION OF PLASMOID IN MAGNETOTAIL**

***Slingshot effect due to tension of magnetic field lines***

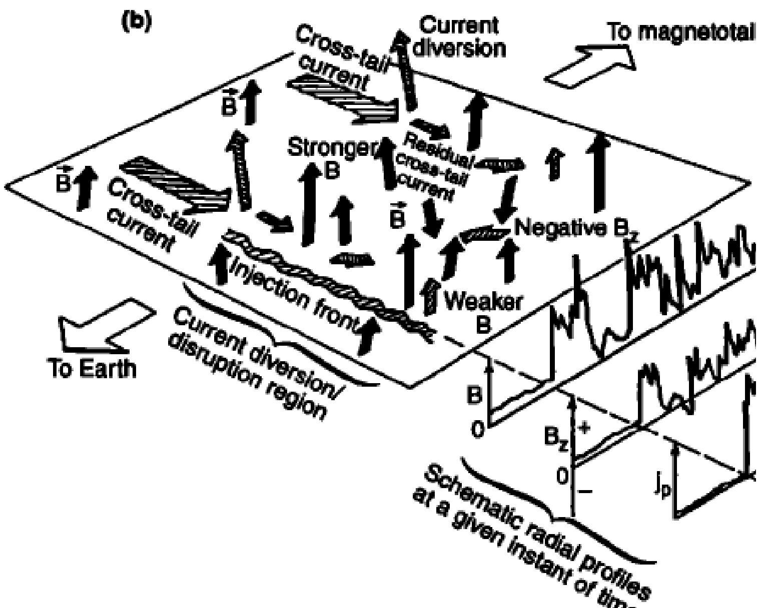
# Near Earth initiation

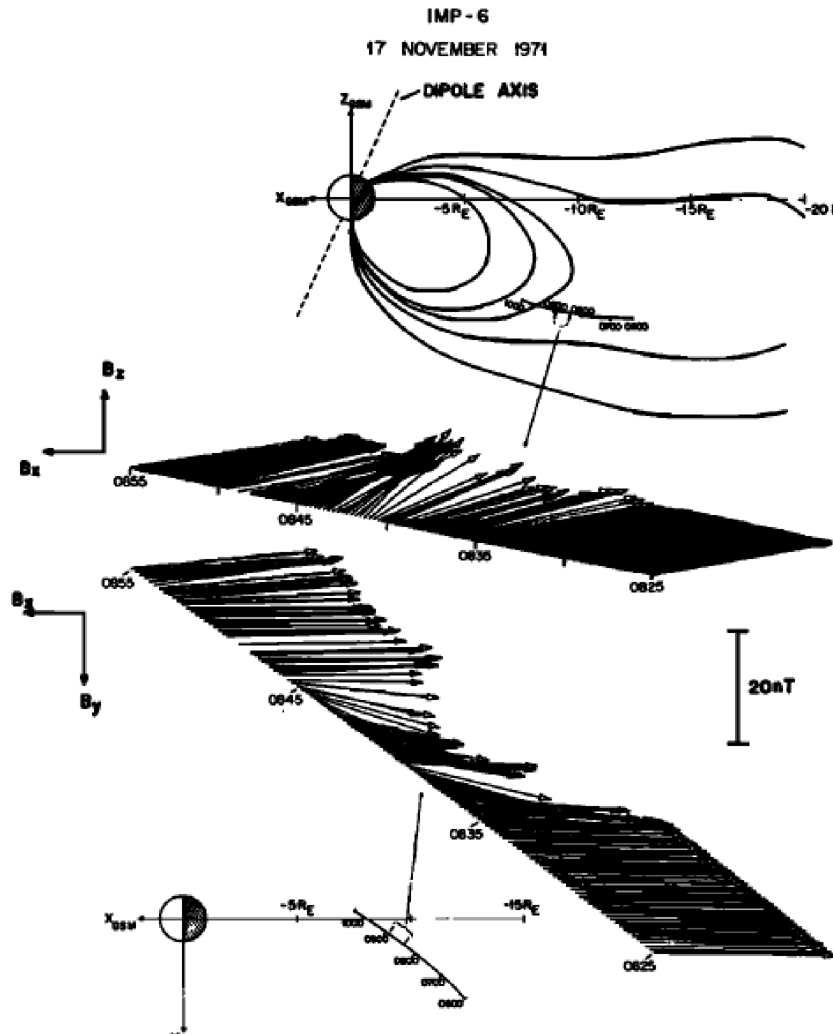


A. T. Y. Lui

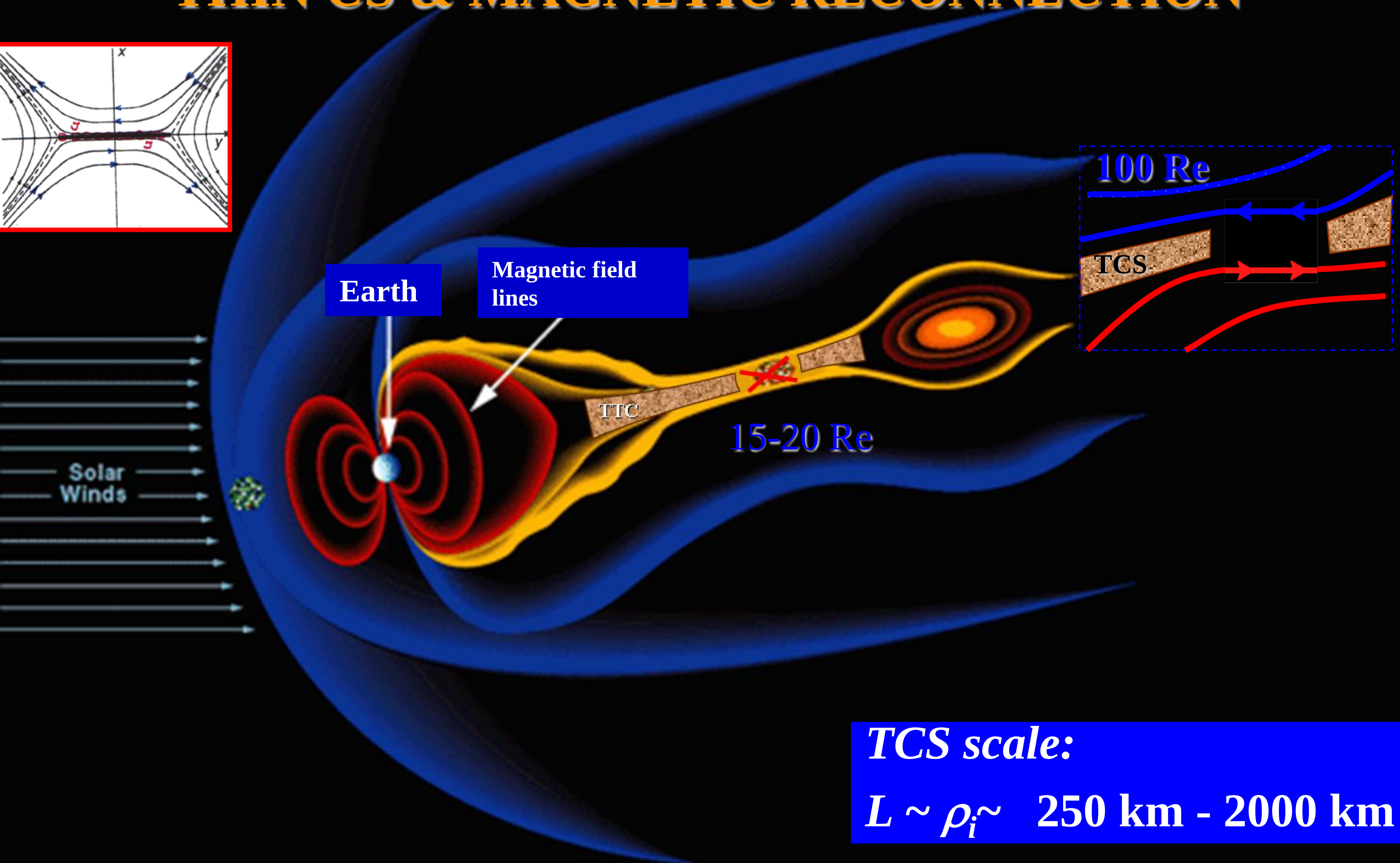



Current disruption in the Earth's magnetosphere: Observation and models.
A.T.Y. Lui, JGR, 1996



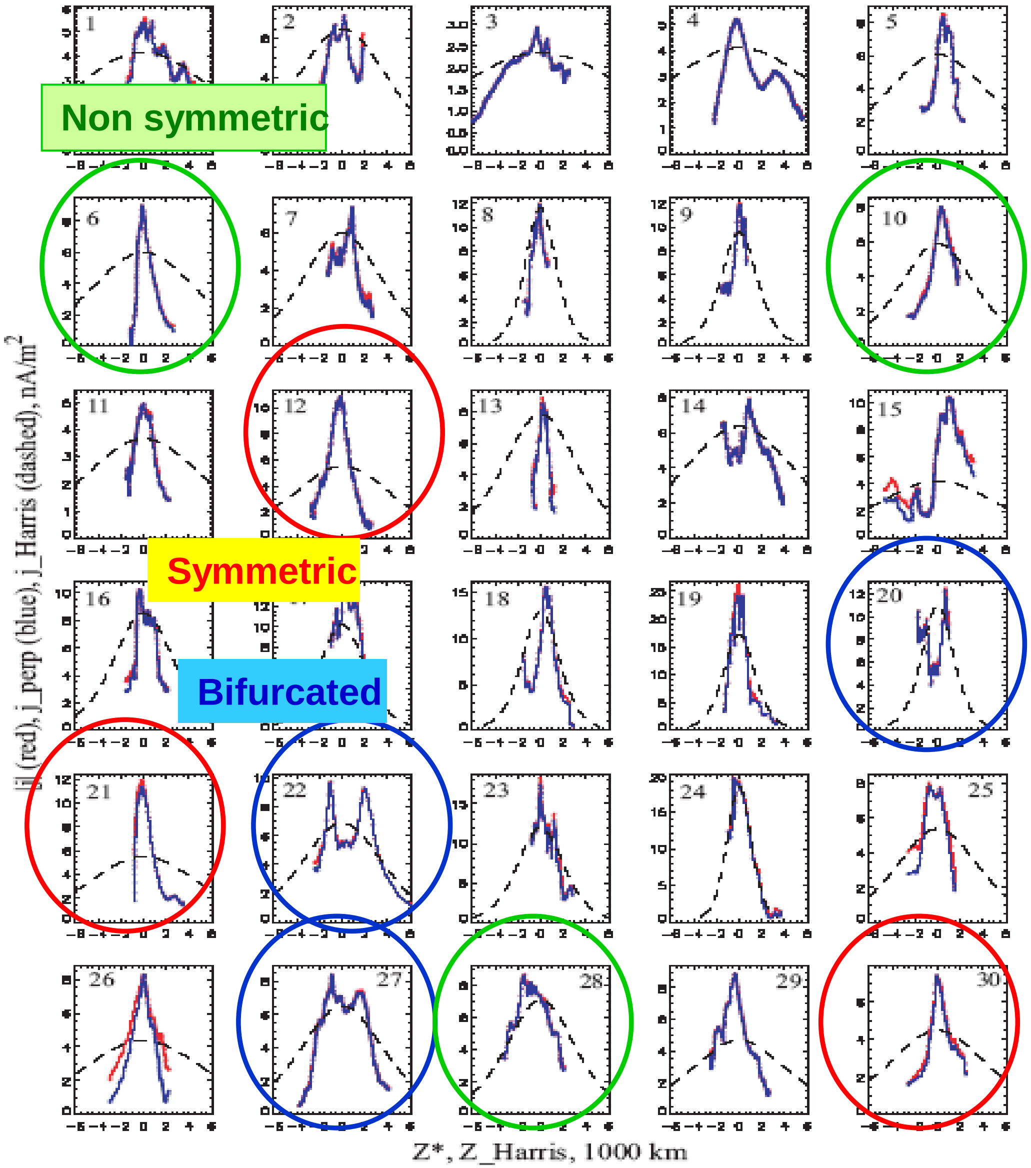



# COEXISTENCE OF 2 PARADIGMS
# THIN CS & MAGNETIC RECONNECTION




***TCS scale:***

***L*** **~** $\boldsymbol{\rho_i}$**~ 250 km - 2000 km**



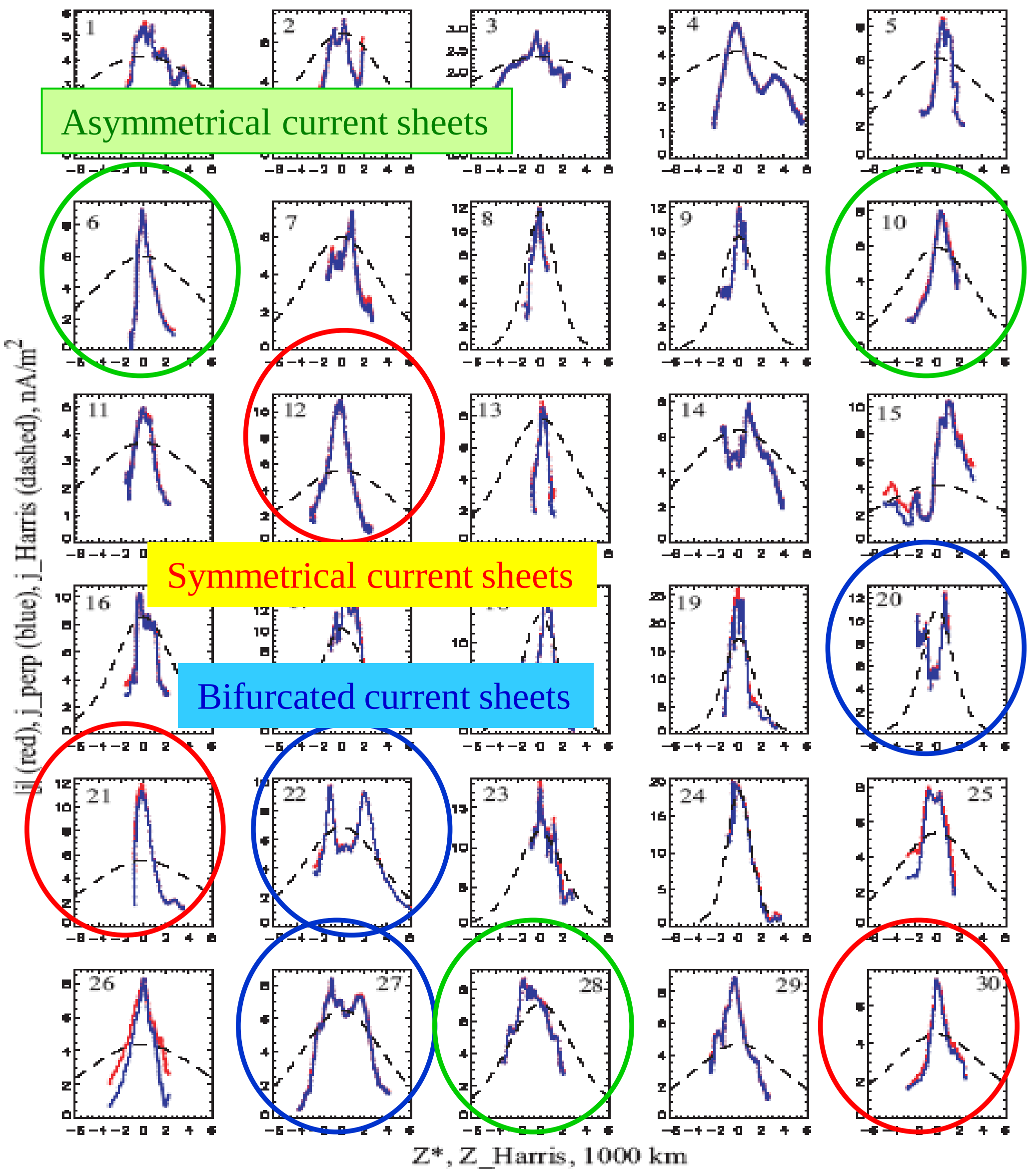

Profiles of absolute values of the current densities $j$ (blue) and $j_\perp$ (red) versus the effective vertical coordinate $Z^*$, calculat
Dashed lines show the corresponding Harris profiles.

# CLUSTER
# " in situ"
# Current Sheets
# OBSERVATIONS

*(RUNOV collection)*

# The observed current sheets are non-Harris ones!!!

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




Profiles of absolute values of the current densities $j$ (blue) and $j_\perp$ (red) versus the effective vertical coordinate $Z^*$, calculat
Dashed lines show the corresponding Harris profiles.

CLUSTER = 4 s/c mission curlometer

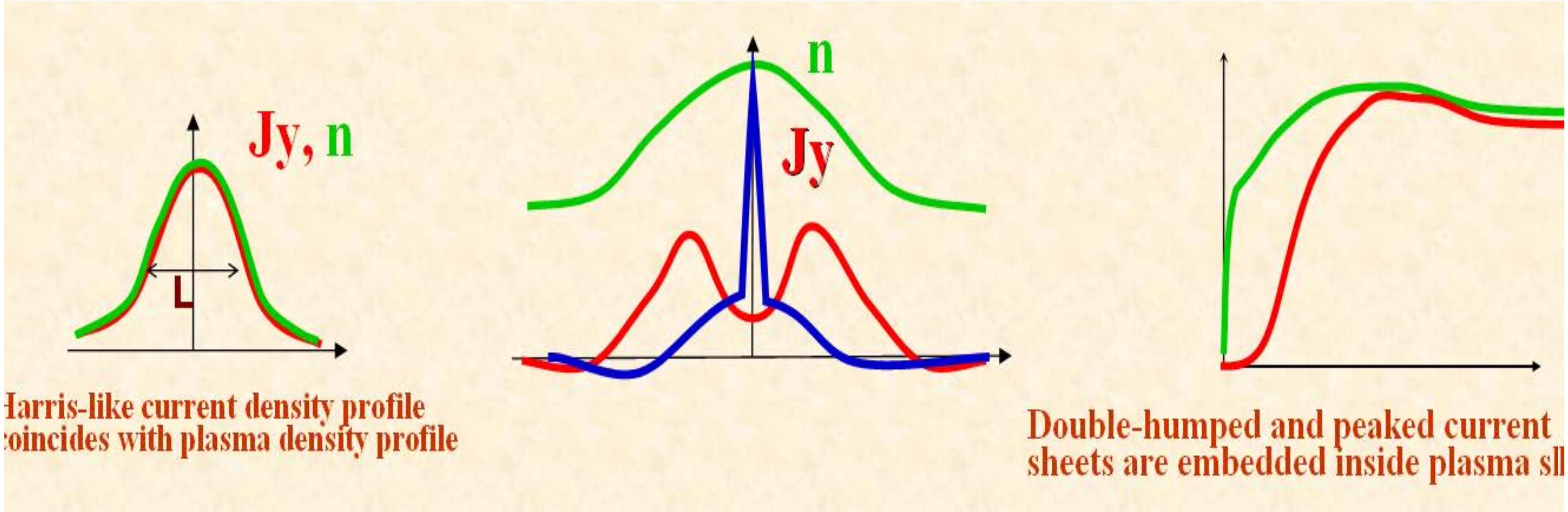
From 2000 year.

Distance from the Earth ~19 $R_E$


1) As a rule TCS are observed during the phase of energy accumulation
2) TCS are embedded inside more thicker plasma sheet
3) The ion distributuion functions are anisotropic
4) Very small thickness about 1-2 gyroradius $p^+$
5) 1-2-3-peaked profiles of current density
6) The presence of heavy ions

Multitude of current shapes Jy(z)

# KINETIC PECULIARITIES:




1. Bifurcation (Splitting of CS)

2.Embedding (enclosed structures)

3.Electron current quasisingular layers

4.Oxygen broadening

5.Assymmetry

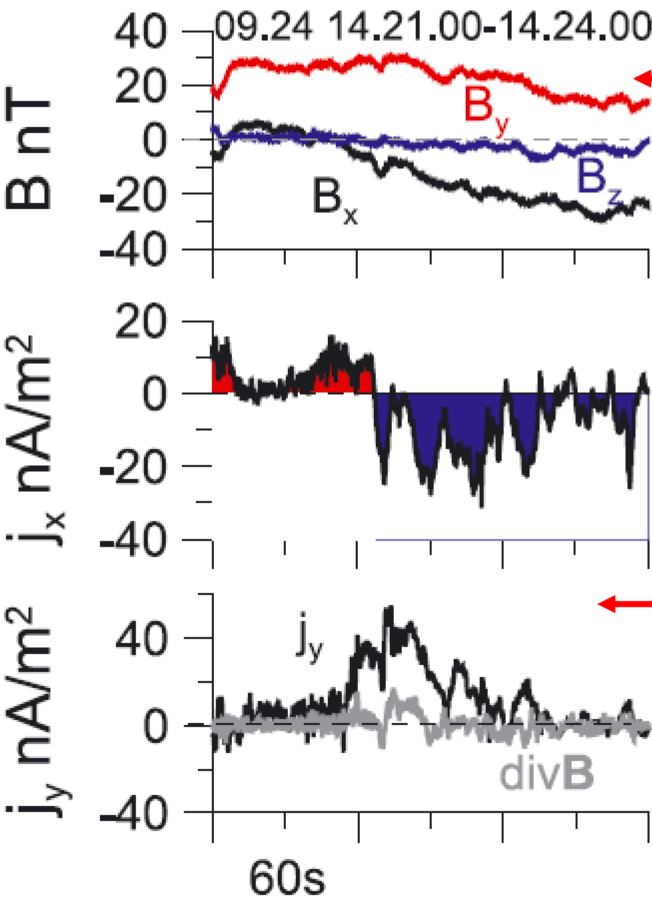
- $O^+$ ions may play a role in substorm triggering ?

  *(e.g., Baker et al., 1982 ; Cladis and Francis, 1992)*

- $O^+$ ions may increase characteristic thickness of TCS ??!!

**The model of a multiscale embedded thin current sheet: "Matreshka" model**

# Internal structure of sub-ion current sheets (STRONG SHEAR)

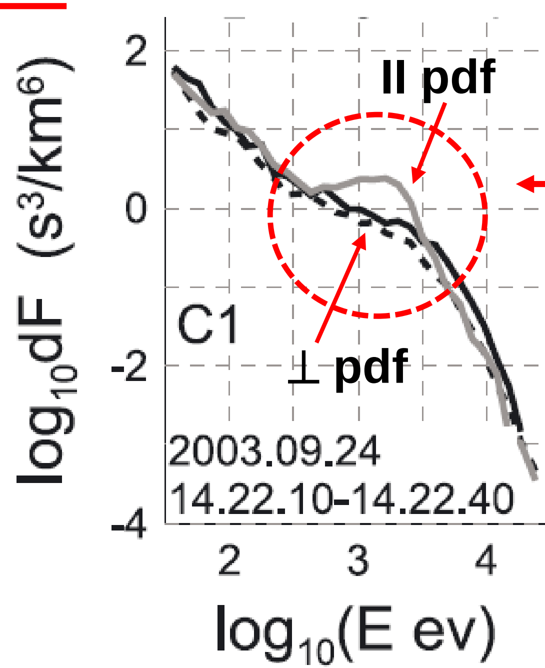



**Strong shear magnetic field is localized in the central region of CS**

**Asymmetrical jx currents**

**Strong jy maximum in the central region of CS**

Electron distribution functions in the central region of CS



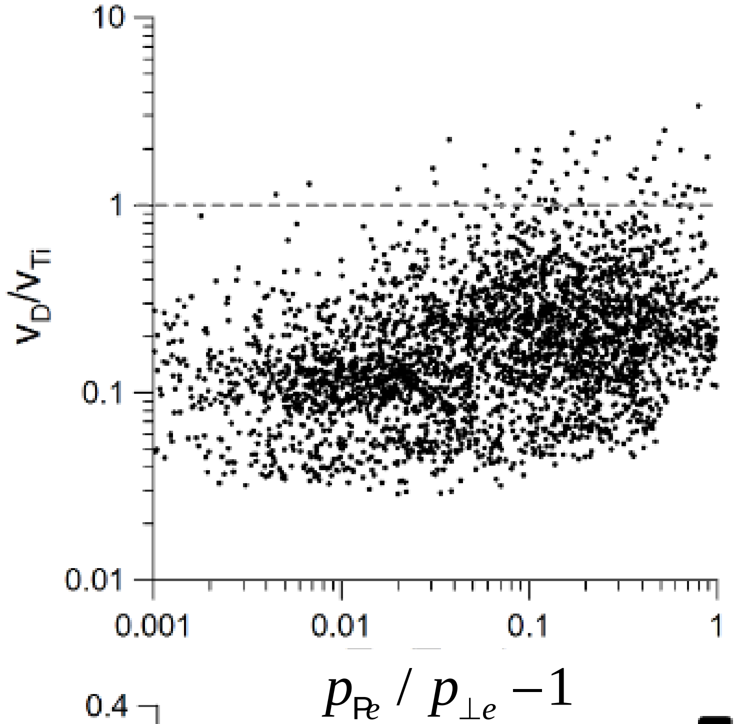

**Strong parallel beams of electrons!** Possible contribution to the parallel current density ~jy due to strong By

# Electron curvature currents

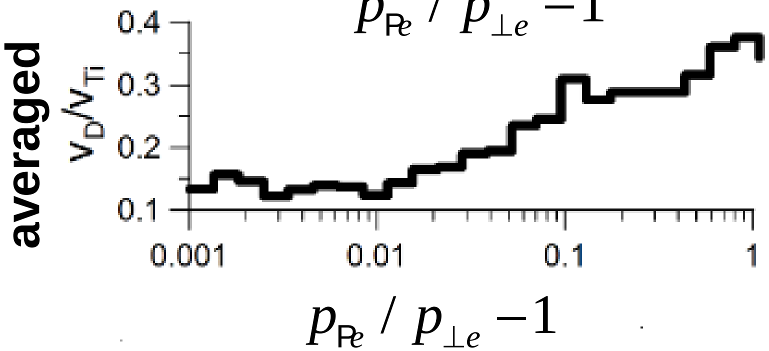
$$\boxed{\frac{4\pi}{c} j_{\perp y} = B_x \frac{\partial \Lambda}{\partial z} + \Lambda \frac{B_z^2 + B_x^2}{B^2} \frac{\partial B_x}{\partial z}} \quad \& \quad div\mathbf{j} = 0 \Rightarrow j_{\mathrm{P}}$$

**Shkarovsky et al. 1966**

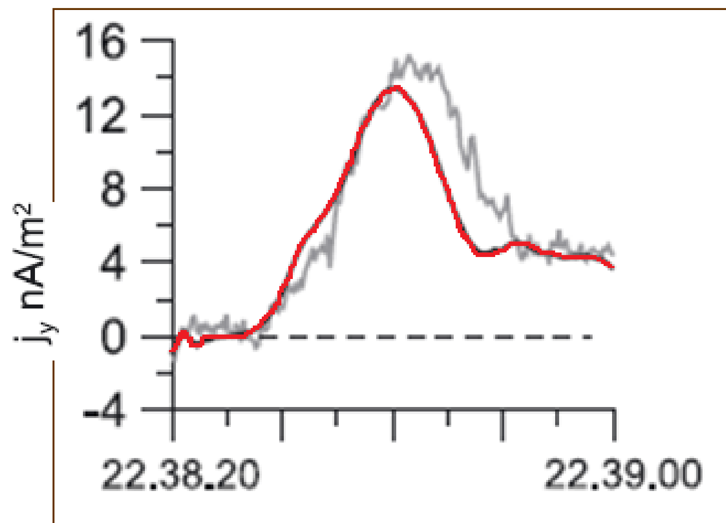
$$\Lambda = 4\pi \left( p_{Pe} - p_{\perp e} \right) \Big/ \left| \mathbf{B} \right|^2$$



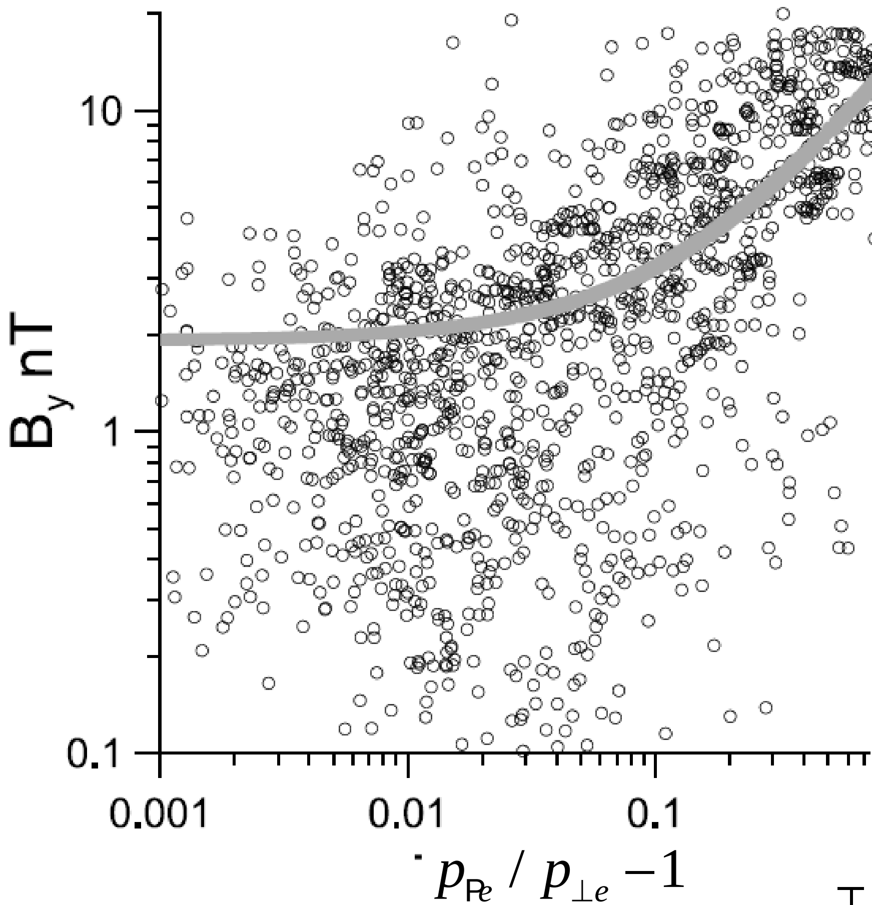

**Increase of electron pressure anysotropy corresponds to increase of curlometer current velocity Vd**



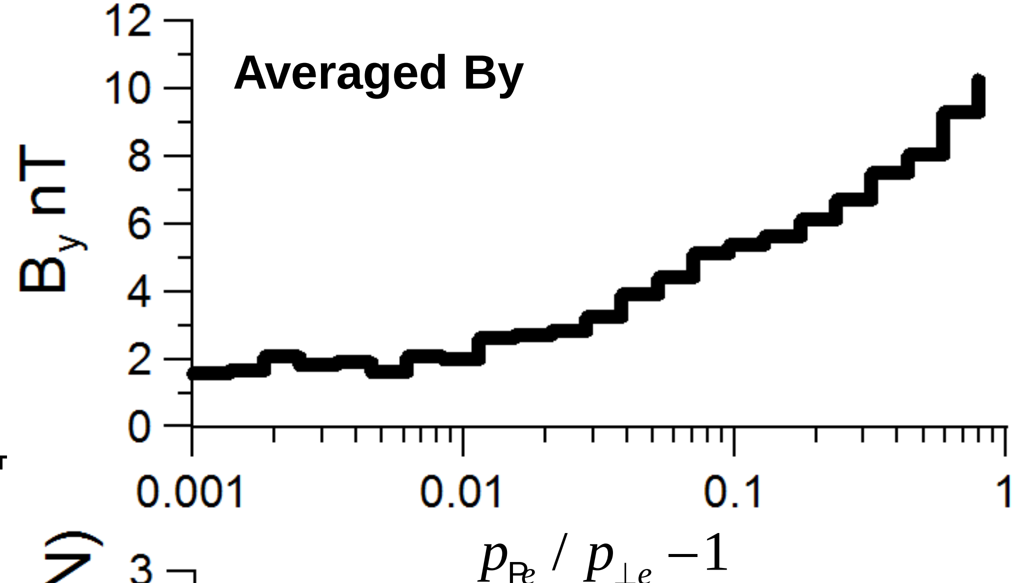

**Example of CS:**
**-curlometer (grey)**
**- electron curvature (black)**
**current densities**

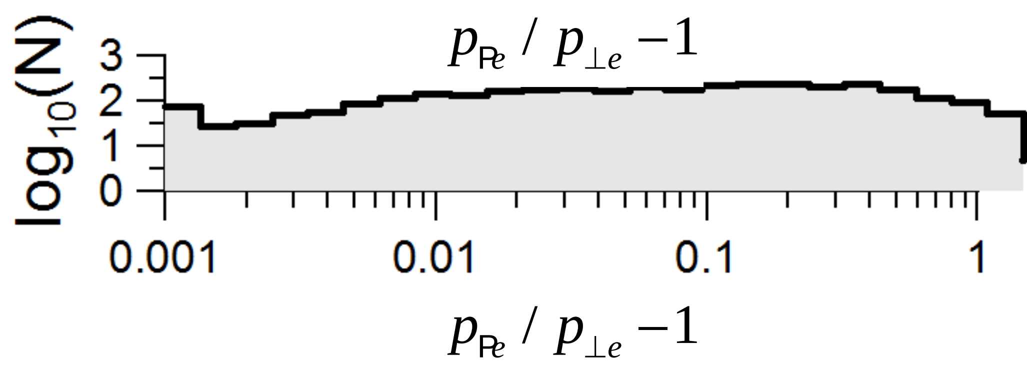


# Generation of shear magnetic field by anisotropic electrons (electron beams?)



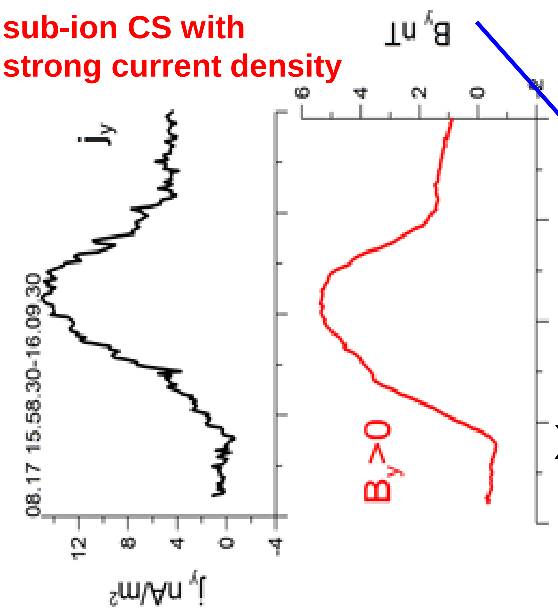

Statistics of intense currents sheets



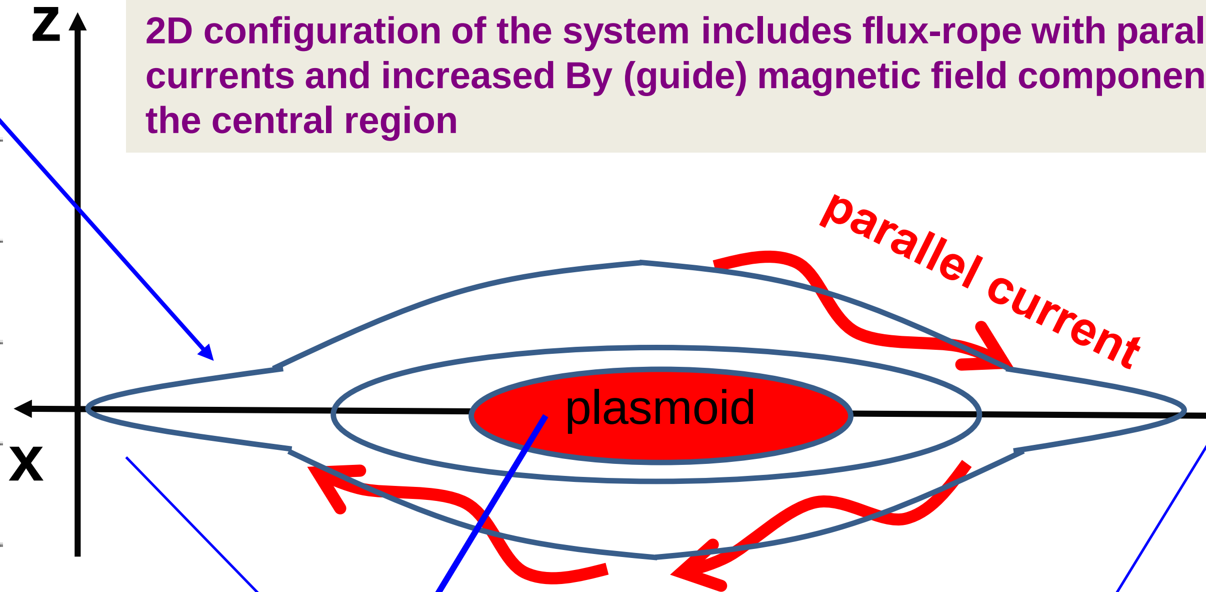



# SELF GENERATION OF SHEAR COMPONENT

sub-ion CS with strong current density

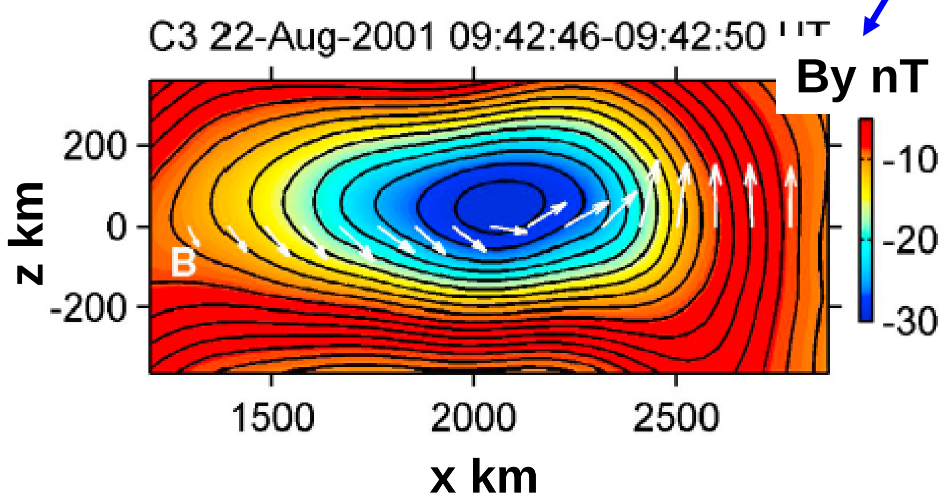



2D configuration of the system includes flux-rope with parallel currents and increased By (guide) magnetic field component in the central region

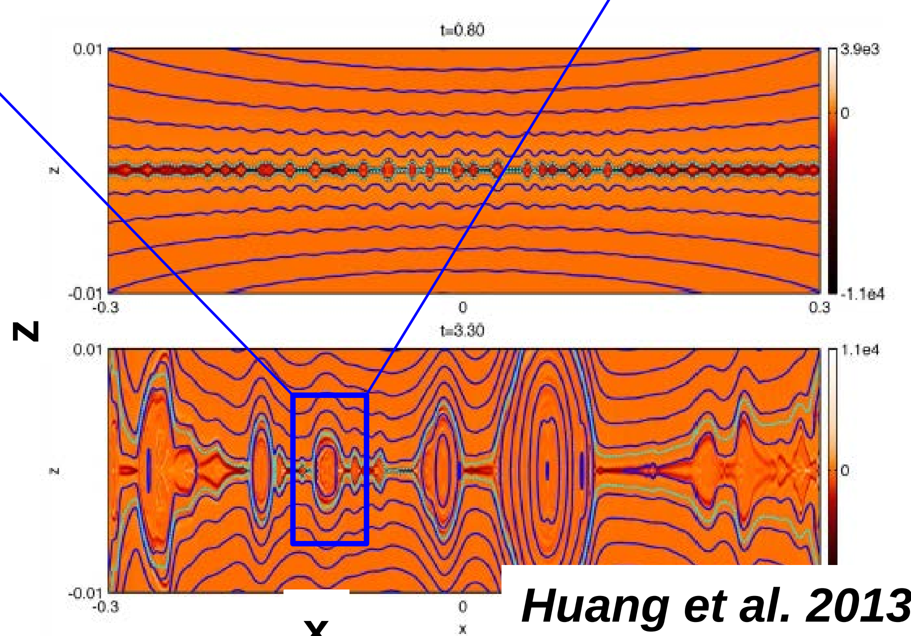



Plasmoid instability of very thin CS

Cluster observations & Grad-Shafranov reconstruction of sub-ion plasmoid




*Teh et al. 2011*

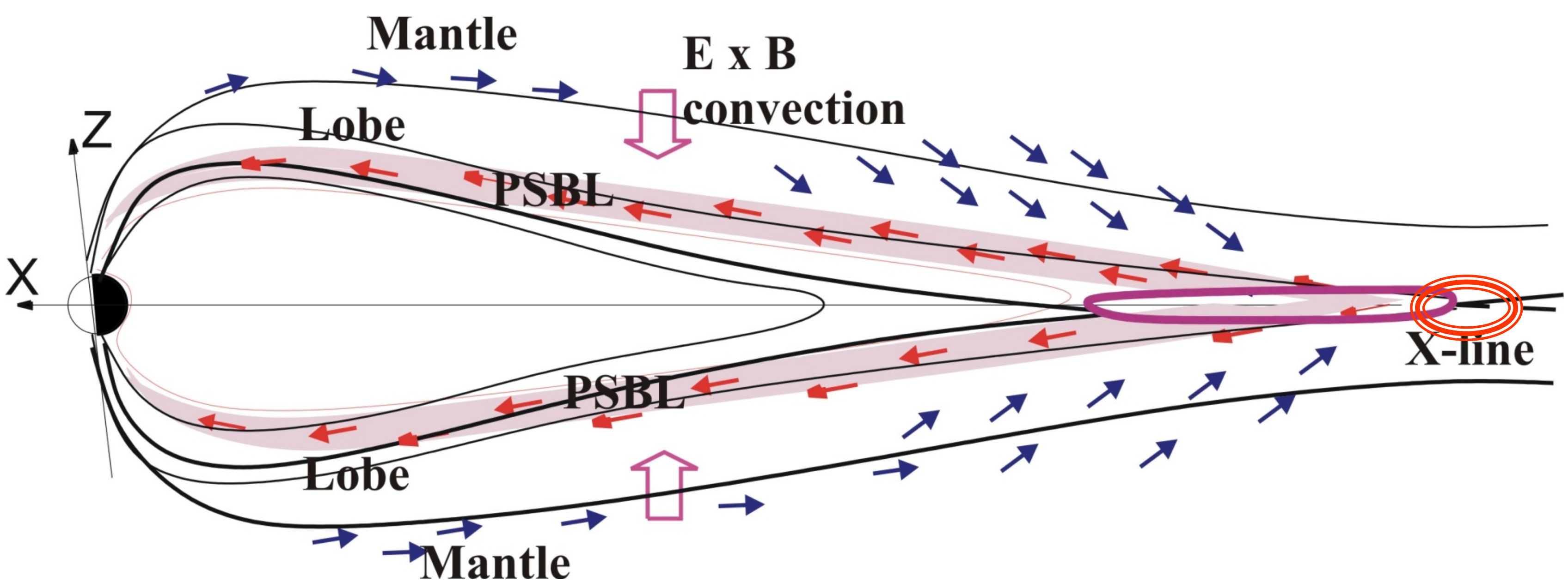



*Huang et al. 2013*

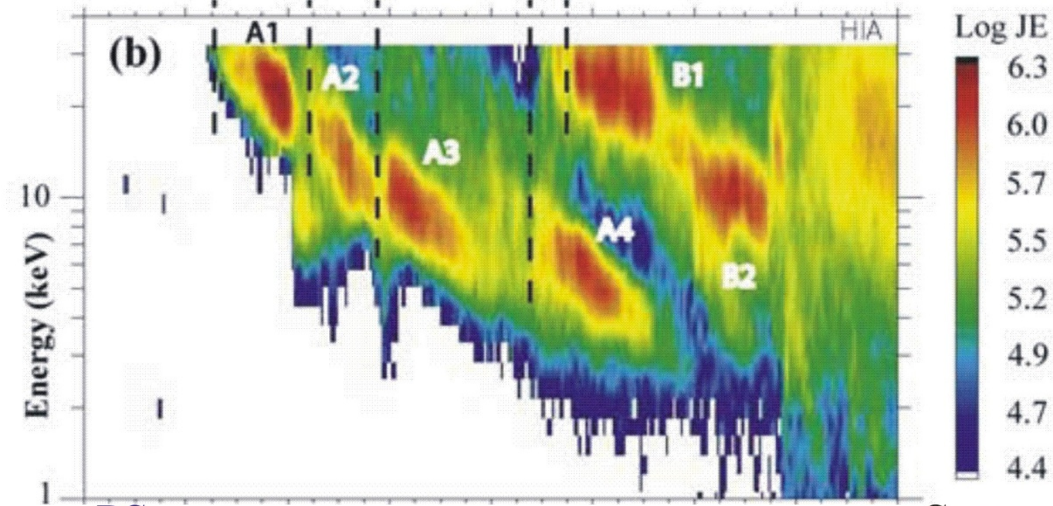
# PSBL-interface between magnetotail lobe and PS.

**High-velocity field-aligned ion beams with parallel velocities $V_{||}$ ~ 500 – 2500 km/s are often observed.**
*(DeCoster and Frank, 1979; Lui et al., 1983; Eastman et al., 1984; Takahashi and Hones 1988; Sergeev et al., 1990, Parks et al., 1998 and ...).*

MHD reconnection: fast plasma flows.
Kinetic model predicts that fast plasma flows consist from small-scale ion beams (beamlets, *Ashour-Abdalla et al*., 1993)



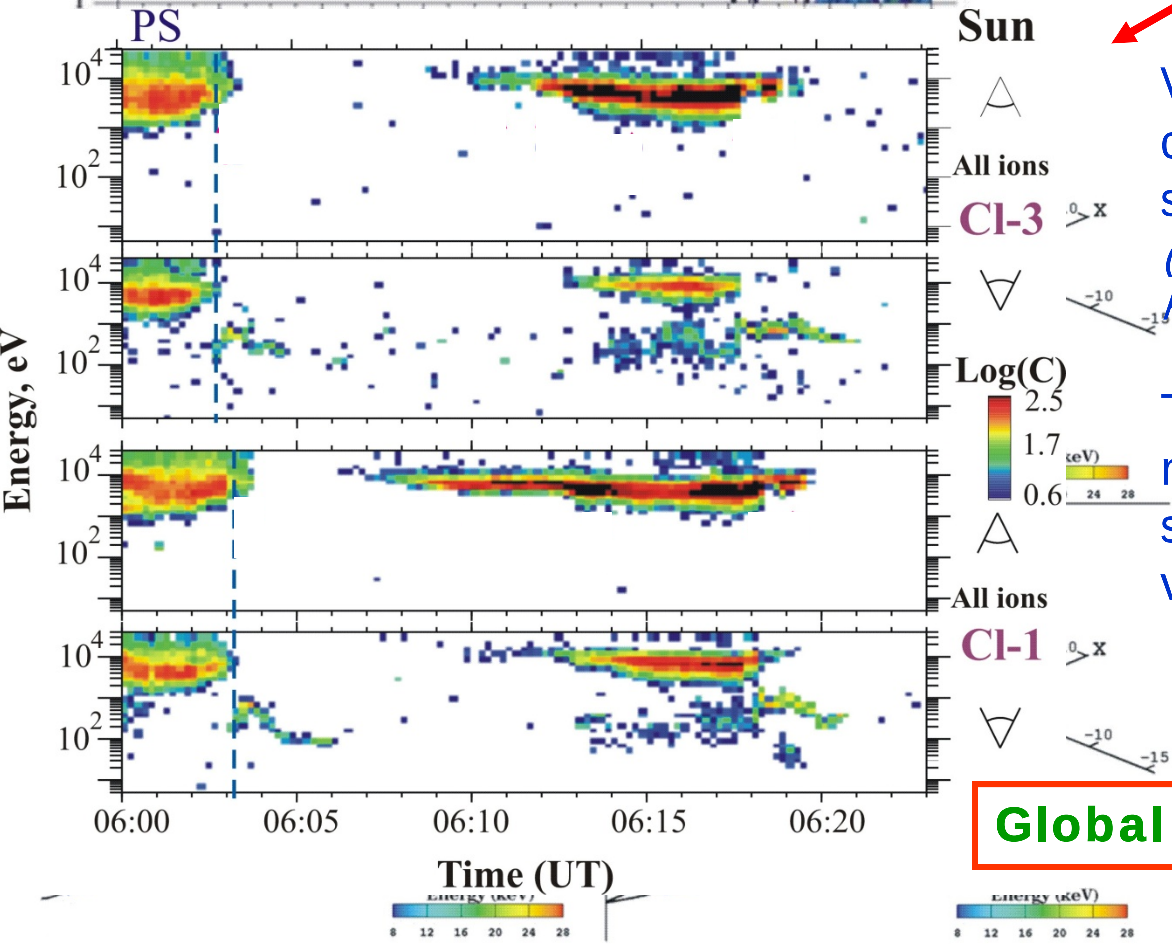

**INTERBALL--- CLUSTER----- GEOTAIL**




## Two manifestations of PSBL-beam structures:

In Auroral Region

In mid-tail




VDIS observed in auroral region consists from several substructures: A1-A4 *(Sauvaud and Kovrazhkin,2004; Keiling et al., 2004)*

Tracing beamlets backward to the magnetotail shows that their sources are located in the wide vicinity of CS X-line

**Global & local energy dispersion?**

# What we have learned else ??
# IN PLASMA SHEET BOUNDARY LAYER

## STRONG TURBULENCE

## VARIETY OF NON- MHD EEFFECTS

*Electrostatic solitary waves

** Nonadiabatic resonant beamlets

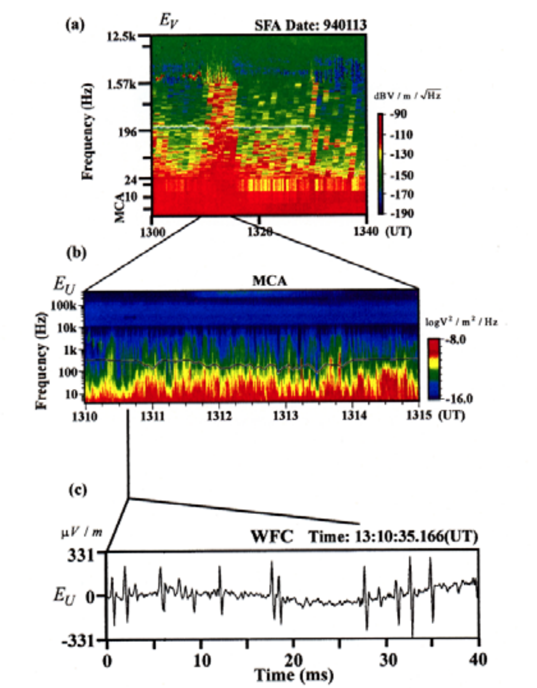
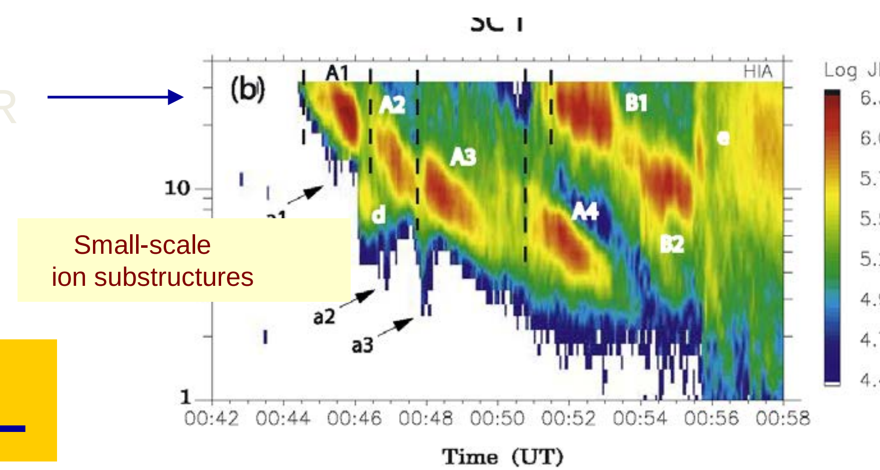
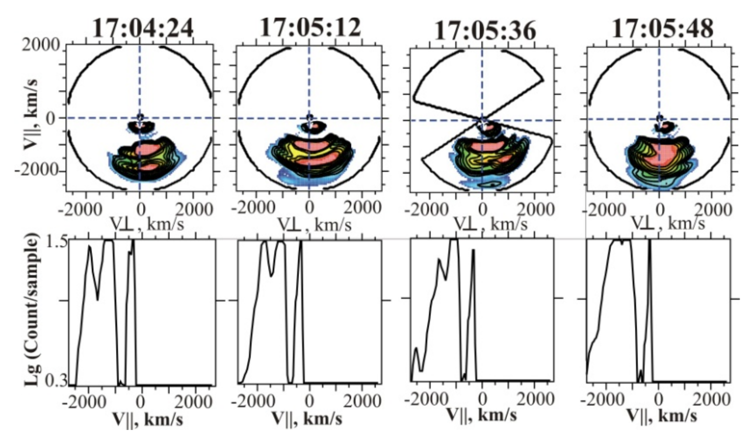



Plate 2. Frequency-time spectrograms for (a) SFA and (b) MCA and (c) waveform of the broadband electrostatic noise (BEN) observed in the plasma sheet boundary layer (PSBL) on January 13, 1994. The isolated bipolar waveforms of the BEN are initially reported by *Matsumoto et al.* [1994b]. They are termed after their waveforms as electrostatic solitary waves (ESW).

CLUSTER

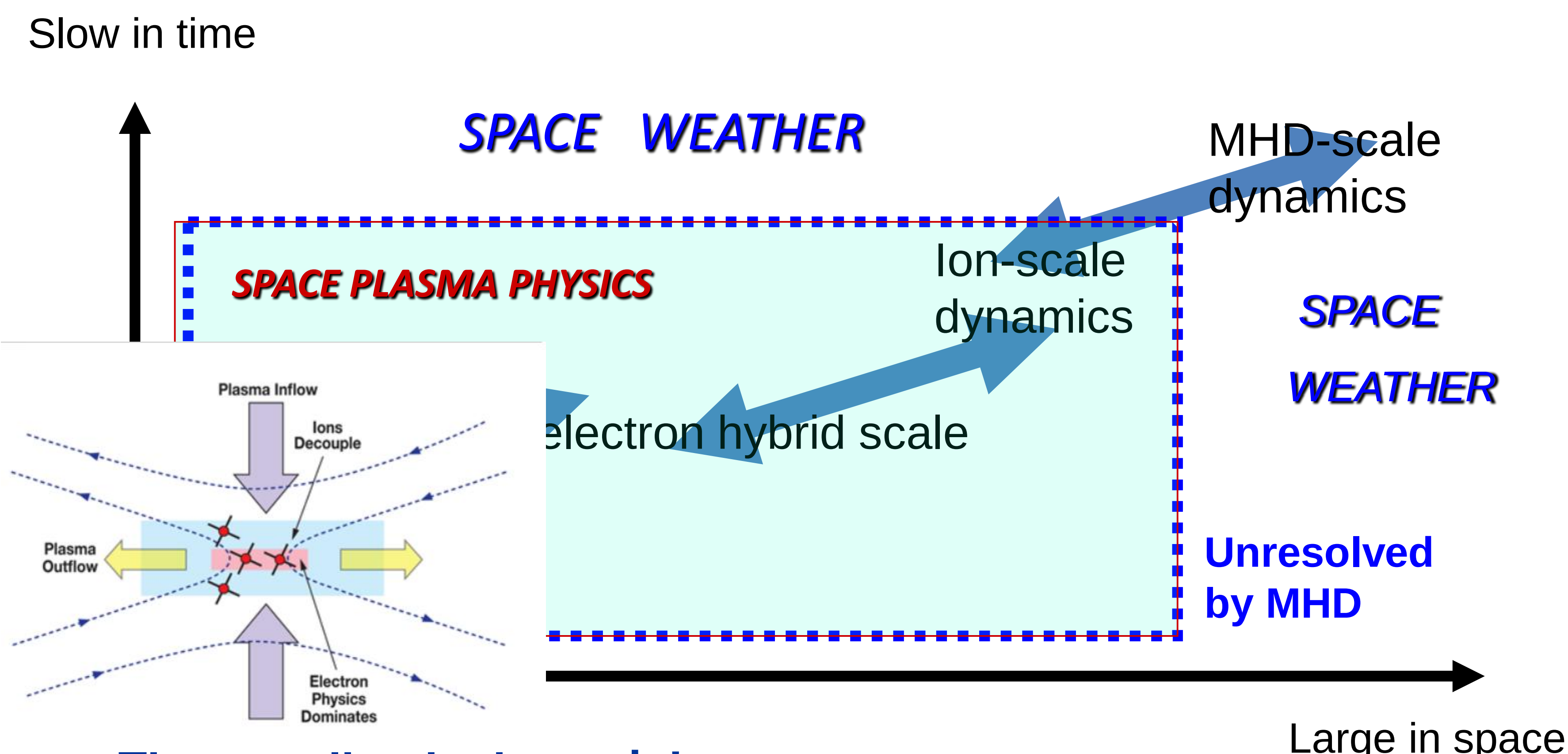
PSBL




GEOTAIL
CLUSTER
THEMIS

# Cross-Scale dynamic Coupling




**The coupling is dynamic!**

**MHD dynamics leads to the formation of the key region and the onset of the key process**

**KINETIC PROCESS ( ~ ION SCALES) DETERMINE THE FINE STRUCTURE OF GLOBAL REGIONS**

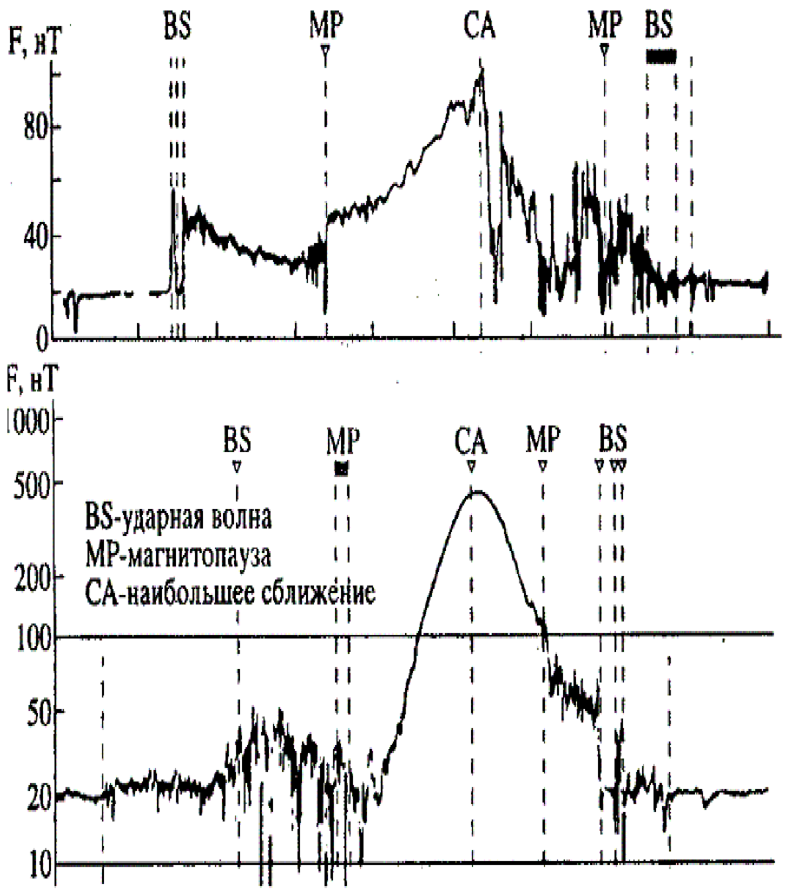
**KINETIC PROCESSES AT ELECTRON SCALES DETERMINE MICROPHYSICS (i.e.RECONNECTION)**

# MERCURY

**Mercury's magnetic field is weaker than Earth's because its core had cooled and solidified more quickly than Earth's**

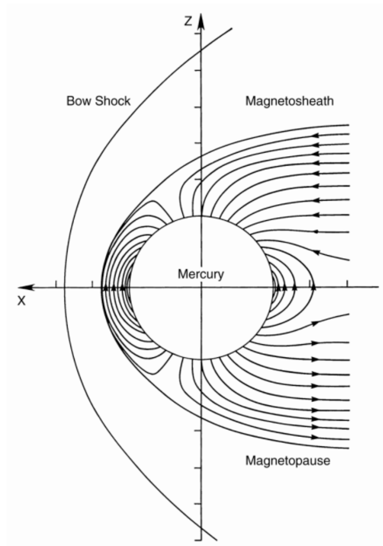
# MERCURY: MAGNETIC FIELD

Mariner-10 flyby measurements 29.03.1974 и 16.03.1975)




Magnetic field might be approximated by dipole
M ~ 1% of the Earth's one

Tilt to rotation axis ~ 7 degrees

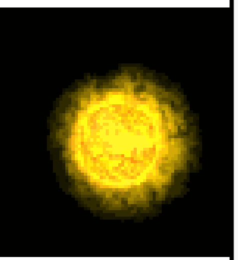


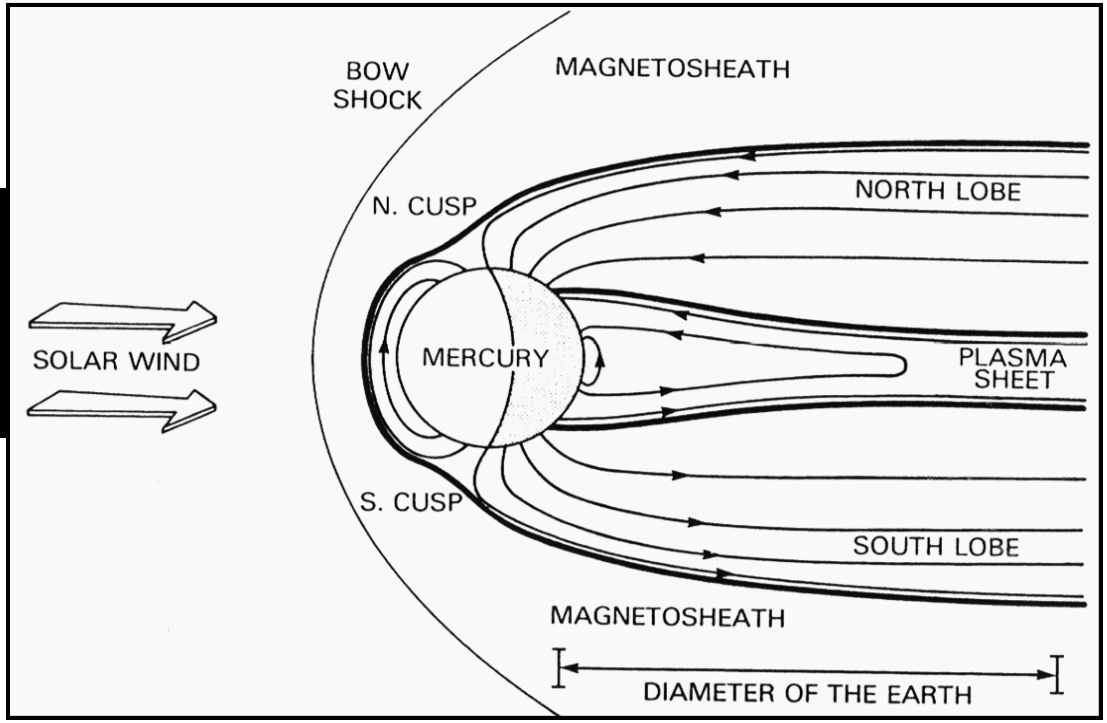

Small Magnetosphere

Size ~ < Ion inertial length

Importance of kinetic effects

# EARTH'S AND MERCURY MAGNETOSPHERES






| Planets | Mercury | Earth |
|---|---|---|
| $V_{sw}$ (km/s) | 400 | 400 |
| $B_{sw}$ (nT) | 20 | 5 |
| $B_T$ (nT) | 40 | 20 |
| $R_p$ (km) | 2439 | 6378 |
| $R_m$ ($R_p$) | 1.6 | 10 |
| $T_c$ | 2 min | 1.1 hr |

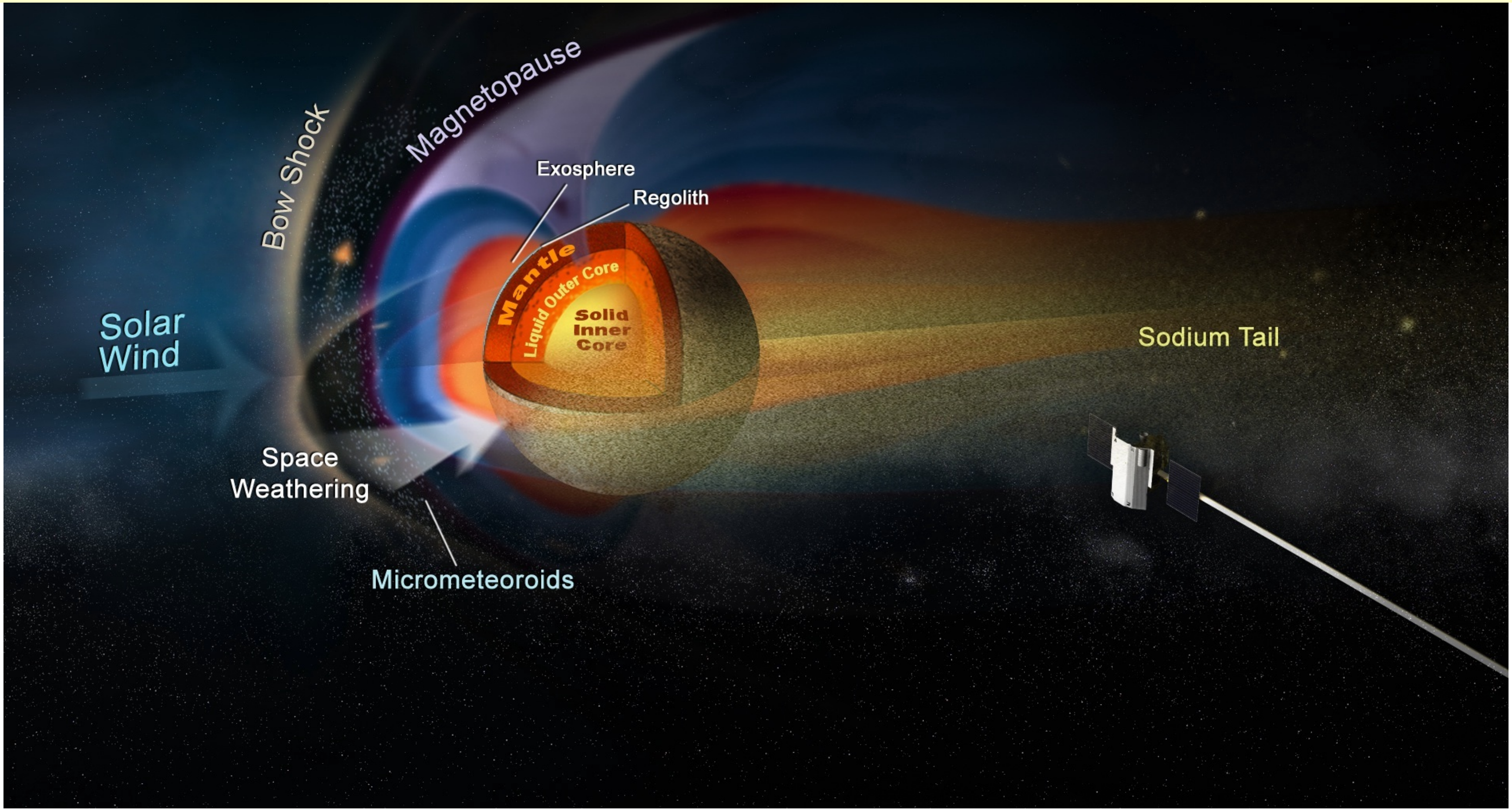
*Ip, 1997, Lundin, 1997*

**MAIN CHARACTERISTICS OF HERMEAMN MAGNETOSPHERE**

1) **SMALL SPATIAL SCALE(1:8)**
2) **3) FAST MAGNETOPLASMA PROCESSSES(1:30)**
4) **3) $D_m$~<$L_m$ Particle motion strongly non-adiabatic.** ***MHD ??? Hybrid !***
5) **DIFFERENT BOUNDARY CONDITIONS (SW PARAMETERS**

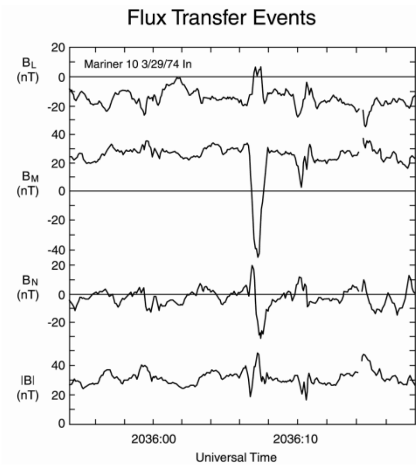
# SMALL BUT COMPLEX AND VERY DYNAMIC MAGNETOSPHERE

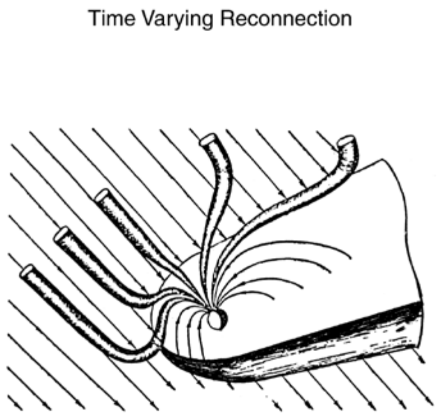
## +EXOSPHERE+SPACE WEATHERING

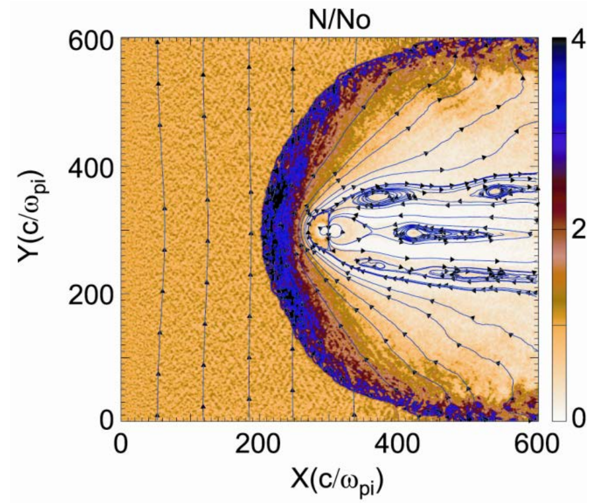



**Rapid reconfigurations**  **Energetic particle bursts**

# Mercury: Magnetopause




**KINETIC EFFECTS- PATCHY RECONNECTION=FLUX TRANSFER EVENTS**

**Relatively large ”quants”of magnetic flux transferred to the night side = strong perturbations- very dynamic tail - Strong inductive acceleration**

# ACCELERATED PARTICLES IN THE EARTH's AND HERMEAN MAGNETOSPERES

## MERCURY

1) **Accelerated electrons~ 600 keV** ***(Eraker and Simpson, 1986)*****. Accelerated plasma flows > 35 keV** ***(Simpson et al., 1974).*** **Duration~10 s., Repetition rate 2-3 min.**

2) **Strongly accelerated protons In Hermean magnetosphere ????** ***(Christon, 1987)*** **?**

## EARTH:

1) **Characterstic energies of accelerated prtons and electrons** $p^{+}$ **и** $e^{-}$

$$E_{i,e} : 1MeV$$

## INDUCTIVE ACCELERATION

in dynamic region of magnetic topology reconstruction

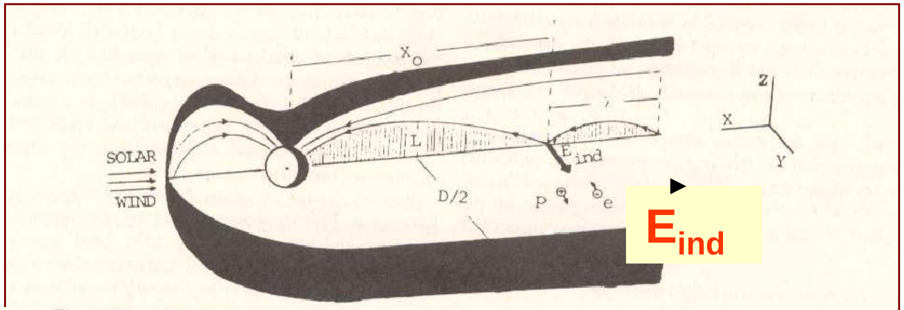



Fig. 1. The model of inductive acceleration in a planetary magnetotail due to the explosive formation of magnetic islands (see text for notations).

$$B = B_{ox} th(z/L)\hat{e}_x + B_z(t) \sin kx \cdot \hat{e}_z$$

$$B_z(t) = B_{0z}/(1 - t/\tau_r) \qquad B_{0z} = B_z(0)$$

ZELENYI ET AL.: BURSTS IN PL

TABLE 1. Mean Values of Terrestrial and Hermean Magnetospheres

| Parameter | Earth | Mercury |
|---|---|---|
| $b_{0z}$, G | $2 \times 10^{-4}$ | $6 \times 10^{-4}$ |
| $\tau_r$, s | 30 | 1 |
| $D$, cm | $\approx 25 \times 10^9$ ($40 R_E$) | $\approx 15 \times 10^8$ ($6 R_M$) |
| $L$, cm | $10^8$ | $6.7 \times 10^6$ |
| $T_i$, keV | 1 | 1 |
| $k^{-1}$, cm | $10^9$ | $6.7 \times 10^7$ |
| $n_0$, $cm^{-3}$ | 1 | 1 |

rot $E_{ind}$=-(1/c)dB/dt

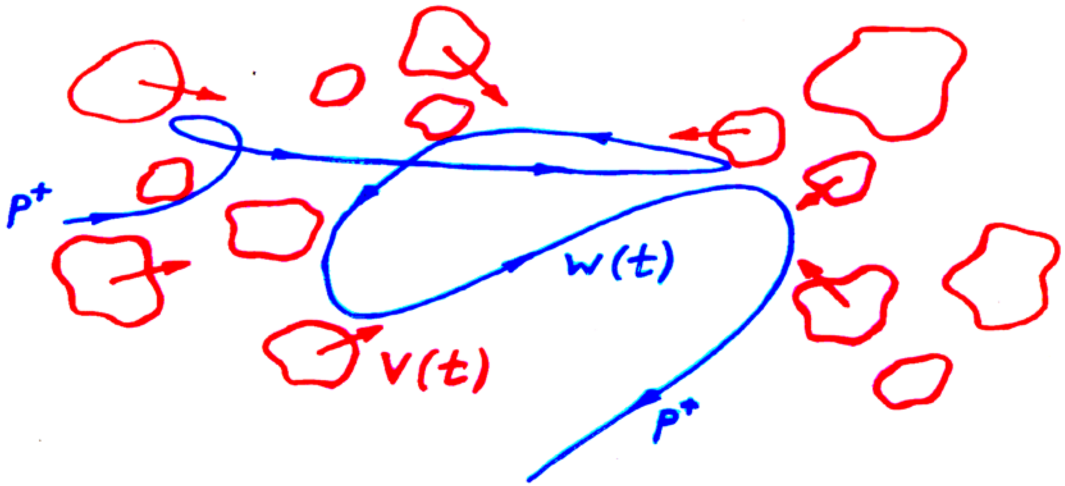
For growing islands directed from dawn to dusk both for Earth and Mercury

For R*~30 scaling

in both cases Eind~5-10mV/m

# Particle acceleration by inductive electric fields

**Coarse-grained system**




- **Nonstationary patterns, appreciably varying with time, support stochastic acceleration phenomena dominating the particle motion**

- **Particle acceleration in time-varying coarse-grained turbulent fields: transport process in velocity space {w}:**

$$\left\langle \delta w^2(t) \right\rangle \nearrow t$$

**PATCHINESS OF ACCELERATION**

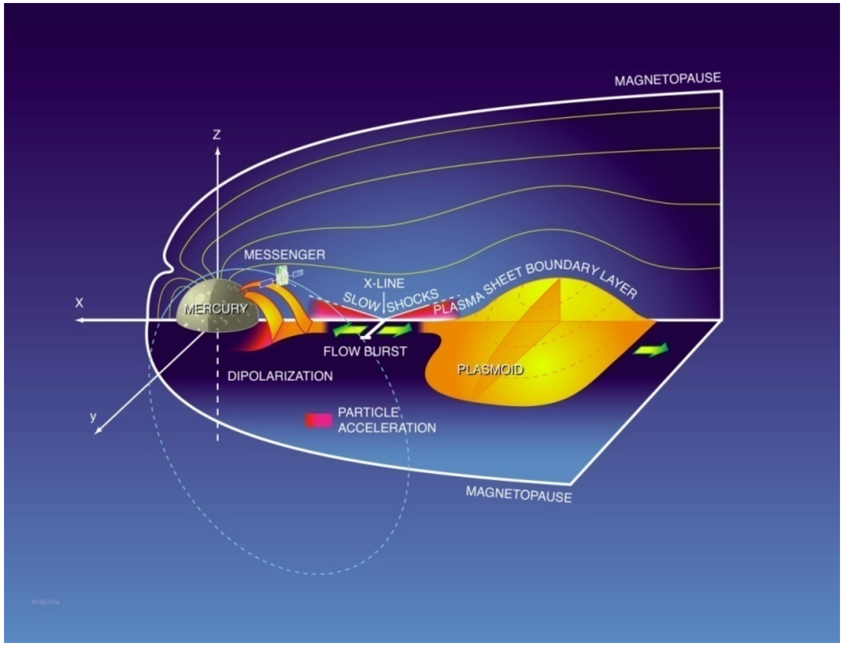
# Comparative results of Bursty acceleration model

## *(THEORETICAL ESTIMATES)*

TABLE 2. Comparison of Observational and Theoretical Values

| Parameter | Earth Observations | Earth Theory | Mercury Observations | Mercury Theory |
|---|---|---|---|---|
| $\varepsilon_e^{max}$, MeV | $\gtrsim 1$ | $\gtrsim 1$ | 0.600 | 1 |
| $\varepsilon_p^{max}$, MeV | $\gtrsim 1$ | 1.6 | ? | 80 |
| $\gamma_e$ | 3.4–8.1 | 4–10 | 7–9 | 4–11.8 |
| $\gamma_p$ | 2–7 | 2–7 | ? | 1.2–1.4 |
| $\tau_B$, s | $10–10^2$ | 50 | 1–2 | 0.2 |
| $\tau_{ss}$, min | 10–60 | 20 | 1 | 0.4 |

**THERE IS NOT ENOUGH ROOM IN A COMPACT HERMEAN MAGNETOSPHERE FOR STRONG ION ACCELERATION**




# Earth-Like Dynamics?

- **Energetic Particle Bursts in the Tail [Simpson et al., 1974]**
- **Substorms [Siscoe et al., 1975]**
- **Magnetospheric plasma heating during substorm-like events [Ogilvie et al., 1977].**
- **Flux Transfer Events [Russell & Walker, 1985]**
- **Substorm-like energetic particle bursts and magnetic field dipolarizations are observed [Christon, 1987].**
- **Magnetic Pulsations [Russell, 1989]**
- **Field-aligned current signature in magnetic field observations [Slavin et al., 1997].**

## Non-Earth-Like Dynamics?

**Lack of a Ionosphere**

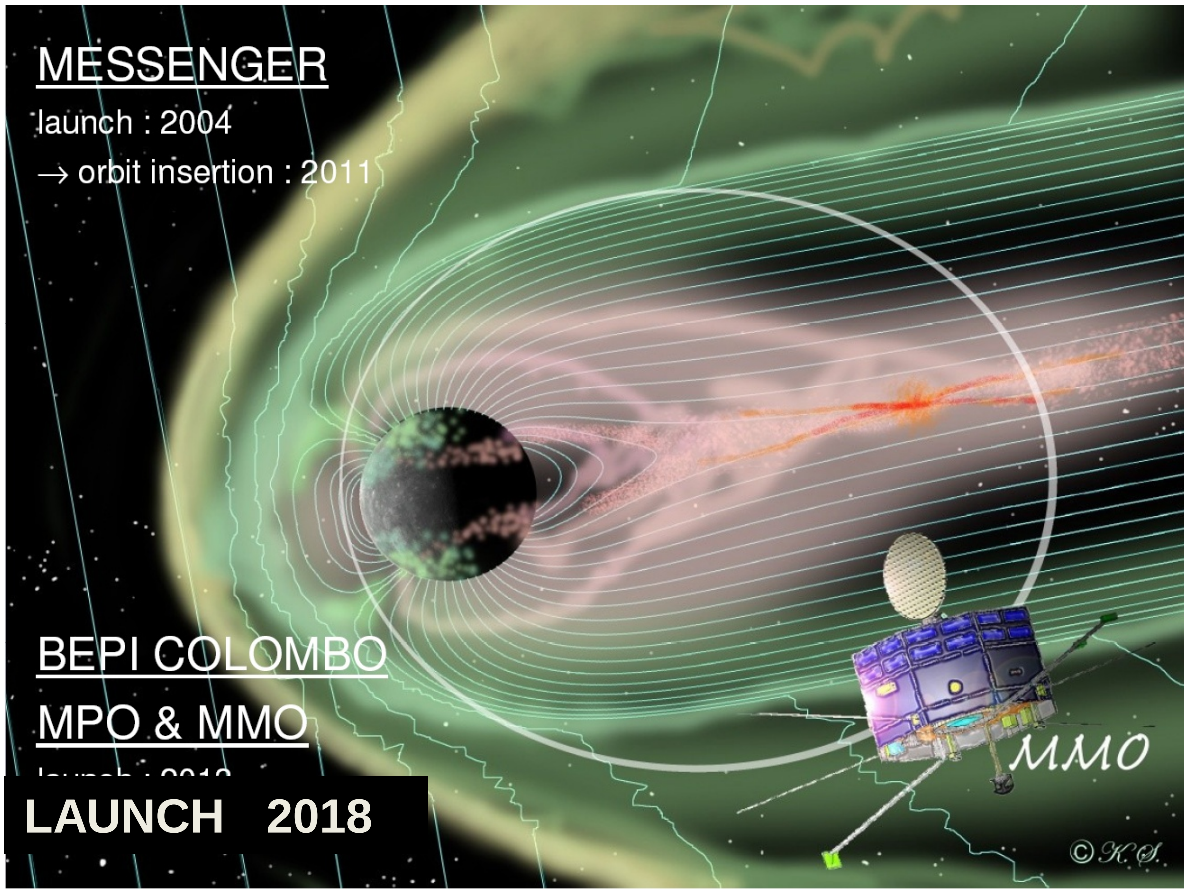
- ***FAC Closure Mechanism***

**Small Dimension**

**Heavy ions**

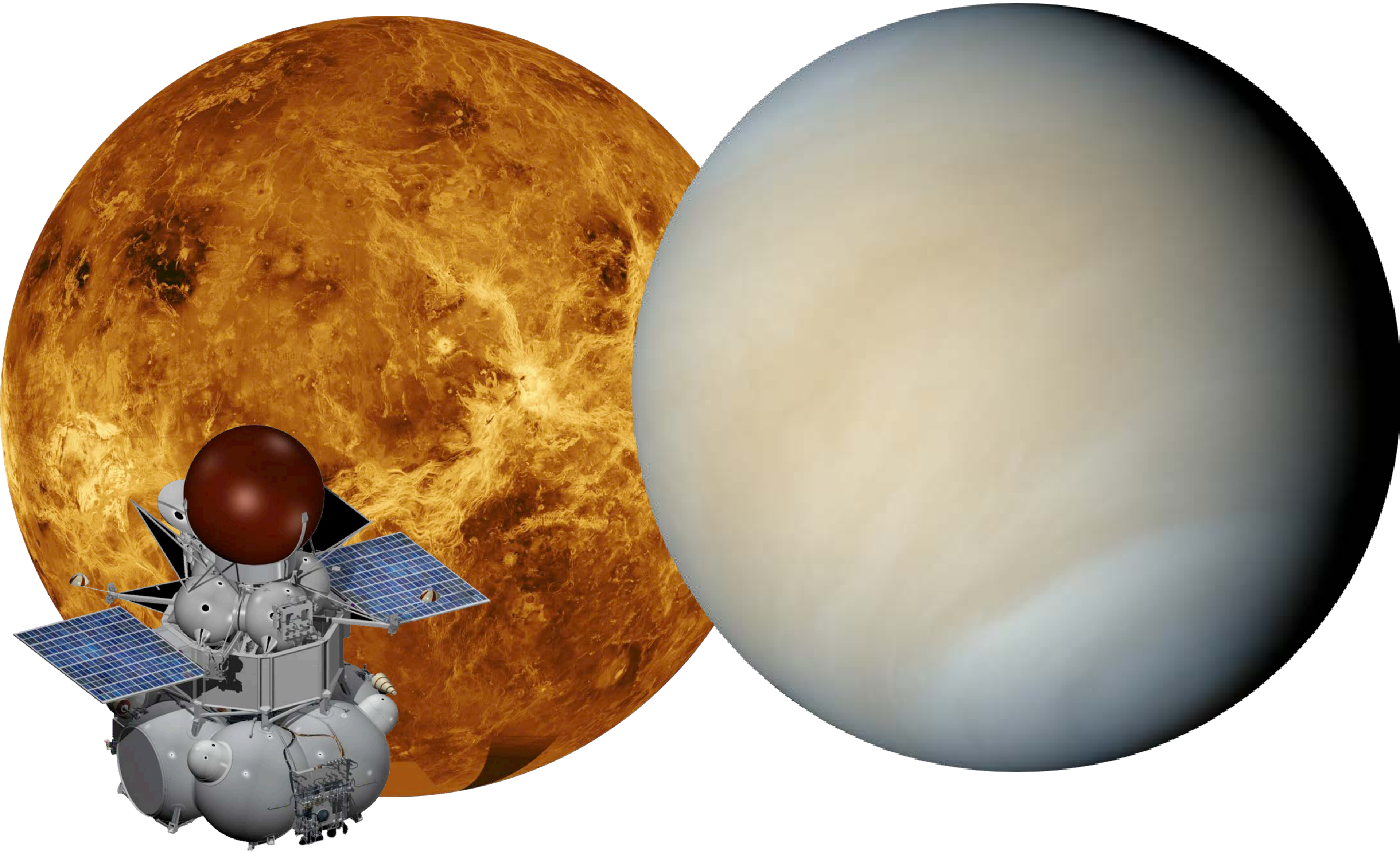
***•Non-Adiabatic vs. Abiabatic Ion motion***
***•Effect on Stress Balance?***
***•Fast time scale substorms***
***•More Patchy Reconnection***
***•Different scenarios of acceleration***

# MERCURY -FUTURE OBSERVATIONS



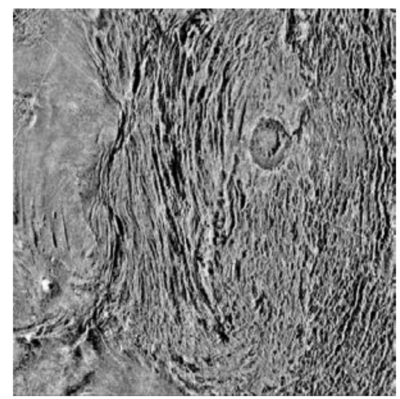

- **Mariner 10 (Orbit III)**
  Inner tail 1974–1975
- **Messenger**
  Polar cap, tail lobe
  Near–Earth plasma sheet
  (Solar wind,
  Magnetosheath)
- **MPO**
  Polar cap,
  Inner tail (→12 RE)
- **MMO**
  Plasma mantle, lobe
  Midtail plasma sheet
  (→ 42 RE)
  (Magnetosheath)

# VENUS

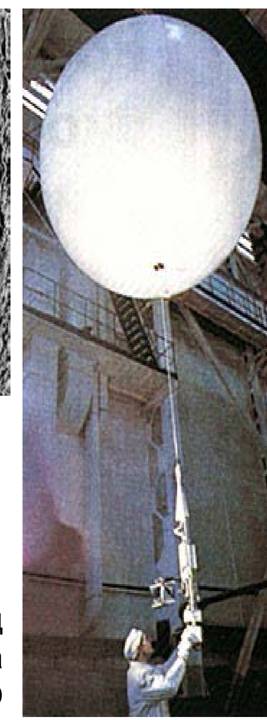


# VENUS "IN SITU"INVESTIGATIONS

| | | |
|---|---|---|
| 1967-1969 | VENUS-4, 5, 6 | • Investigations Descend |
| 1970 | VENUS-7 | **First landing** |
| 1972-1975 | VENUS-8, 9, 10, 11, 12 | **LANDINGS SURFACE IMAGES** |
| 1981 | VENUS-13, 14 | **COLOR PANORAMS SAMPLE ANALYSIS** |
| 1984 | VEGA(+VENERA + HALLEY COMET | **LANDING BALLOONS** |
| 1983-84<br>1989-94 | VENUS -15, 16<br>Magellan | **RADAR SURFACE MAPS** |
| 1978-92<br>2005-15<br>2015- | Pioneer-Venus<br>VENUS_EXPRESS<br>Akatsuki (JAXA) | **ORBITAL INVESTIFATIONS OF ATMOSPHERE SW INTERACTIONS** |

Радарное изображение поверхности (Венера-15)

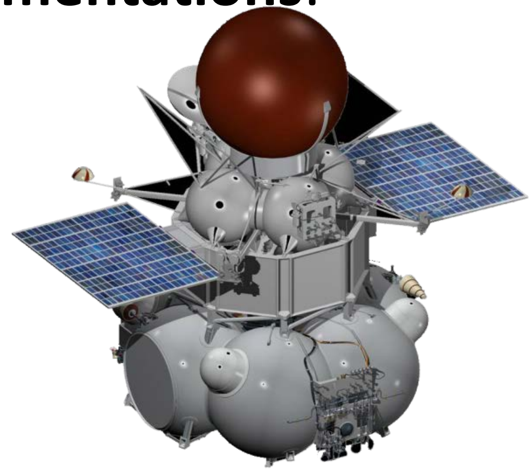


Аэростатный зонд Вега
АО «НПО Лавочкина»

# Venera-D Concept: Mission Elements NASA+RSA

- **Baseline**:
  - Orbiter : Polar 24 hour orbit with a lifetime greater than 3 years—**Can trade orbiter period for mass, SDT has suggested a period of up to 3 days**
  - Lander (VEGA-type, updated) 2+ hours on the surface (one hour to conduct baseline science and one hour of margin)

- **Other components discussed as potential augmentations**:
  - Free flying aerial platform
  - Sub-satellite or nanosats
  - Dropsondes and other platforms



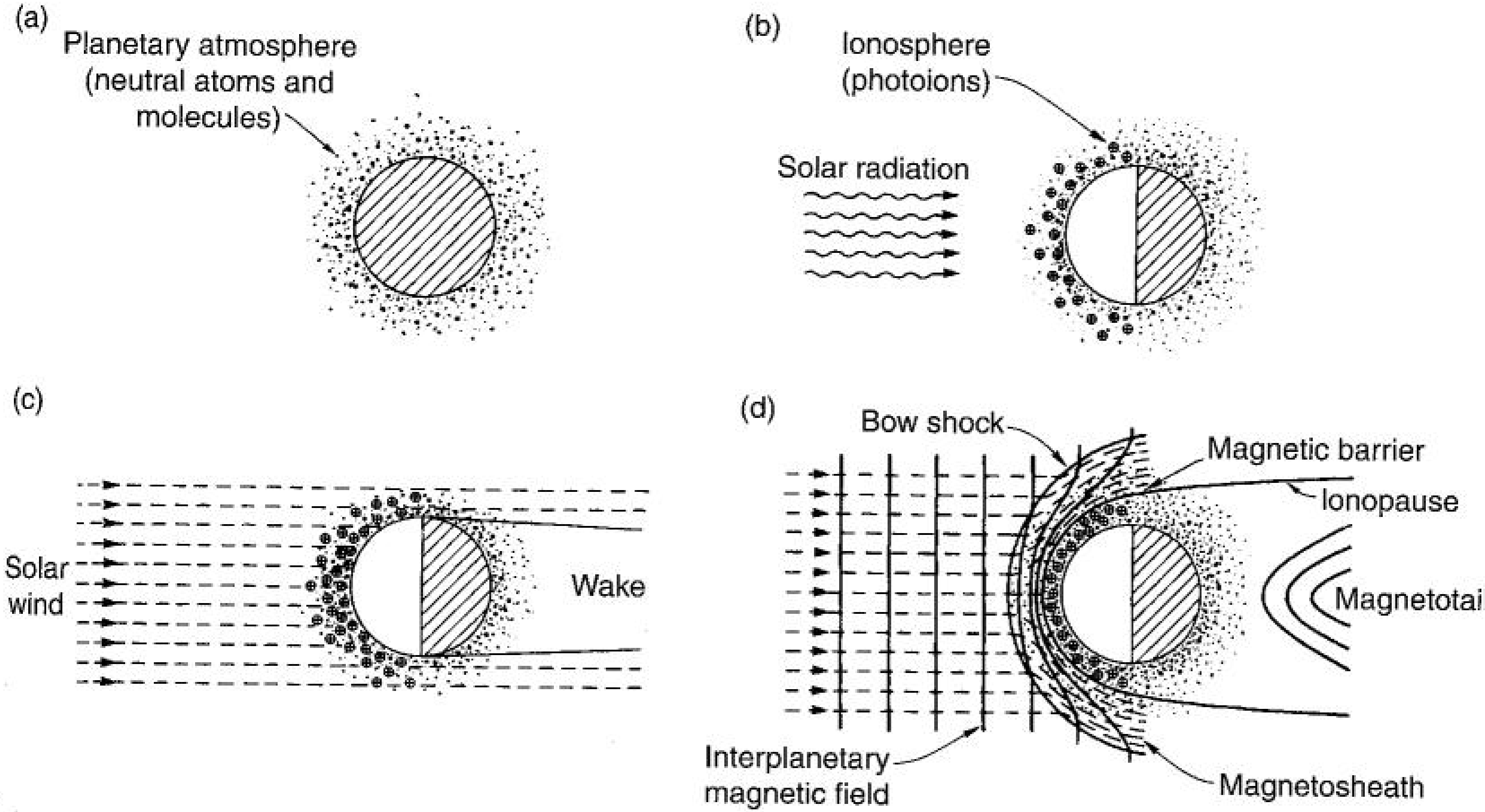


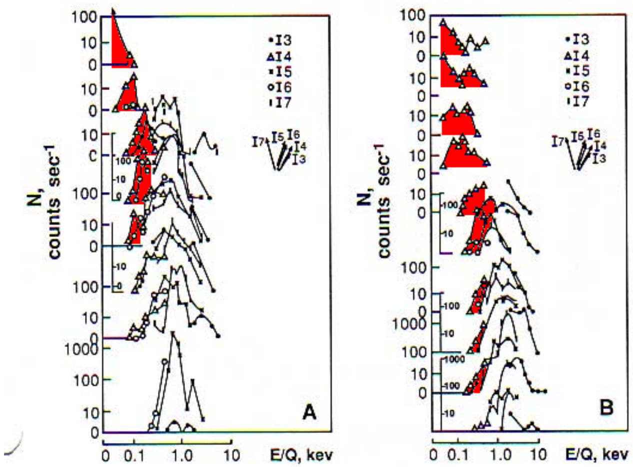

FIGURE 8.4. Illustration of the steps (a) to (d) that lead to the formation of an ionospheric planetary obstacle in a flowing plasma like the solar wind. Ionization by solar radiation, for example, is followed by diversion of the external plasma flow only if that flow is magnetized.

**Illustration of formation of ionospheric obstacle before non- magnetized plane**

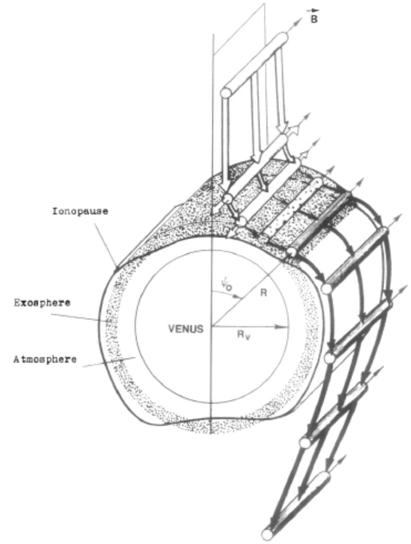
*after Russell and Luhmann (2017)*

# ACCRETION MODEL OF INTERACTION OF SW WITH VENUS

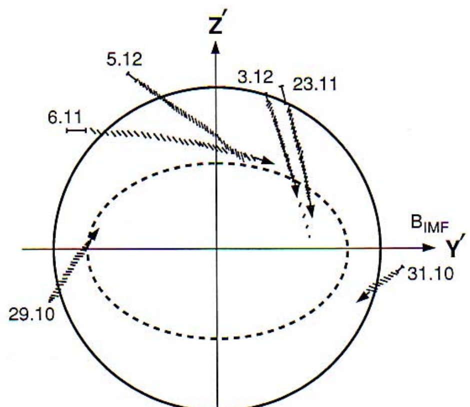
Zwan, B.J., Wolf, R.A., 1976. Depletion of solar-wind plasma near a planetary boundary.

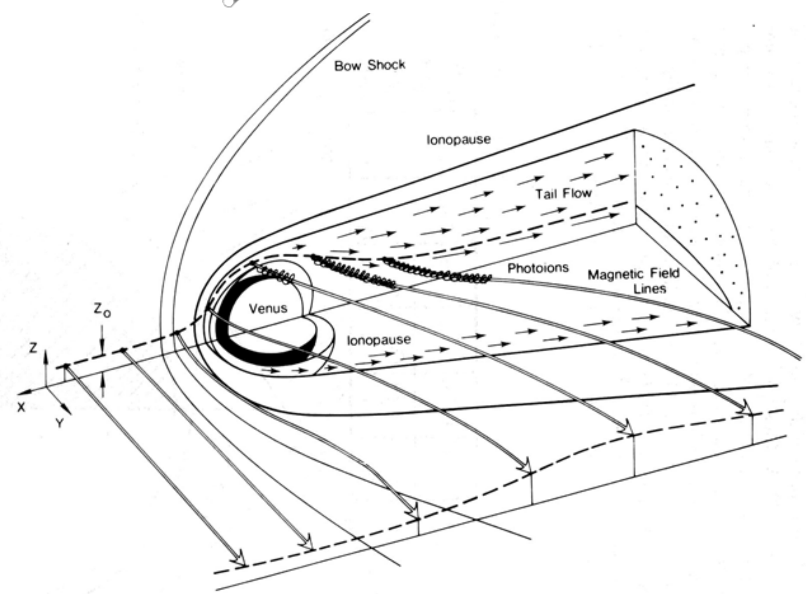



MODEL




Vaisberg, O.L., Zelenyi, L.M., 1984. Formation of the plasma mantle in the Venusian magnetosphere. ICARUS 58, 412–430.
Zelenyi, L.M., Vaisberg, O.L., 1985. Venusian interaction with the solar wind plasma flow as a limiting case of the cometary type interaction. In: Buti (Ed.), Advances of Space Plasma Physics. World Scientific, pp. 59–76.

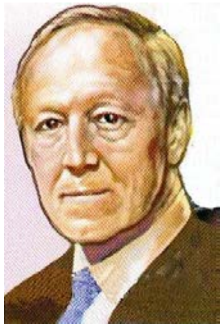


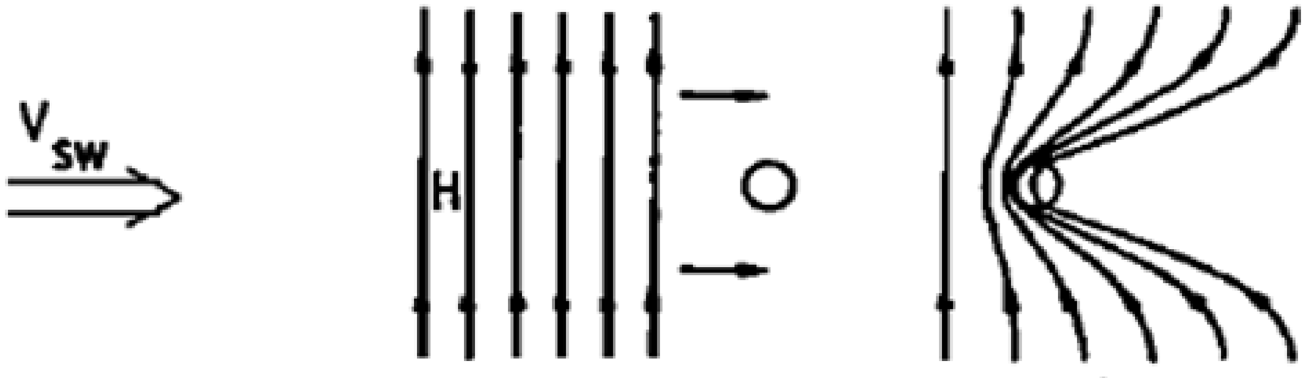




FORMATION OF MAGNETIC BARRIER

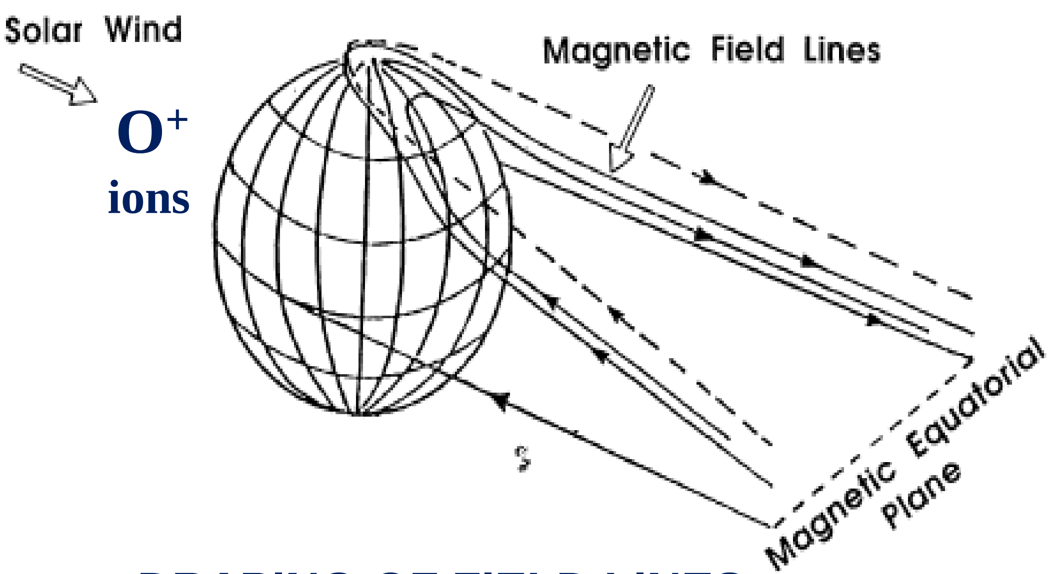
# FORMATION OF VENUS MAGNETOTAIL

(Alfven, 1957)






BENDING OF FIELD LINES OCCURS DUE TO DIFFERENTIAL MASS LOADING OF CONVECTING FIELD LINES




DRAPING OF FIELD LINES

BRAKING OF FLUX TUBES AT MAGNETIC BARRIER DUE TO STRONG LOADING BY PLANETARY IONS

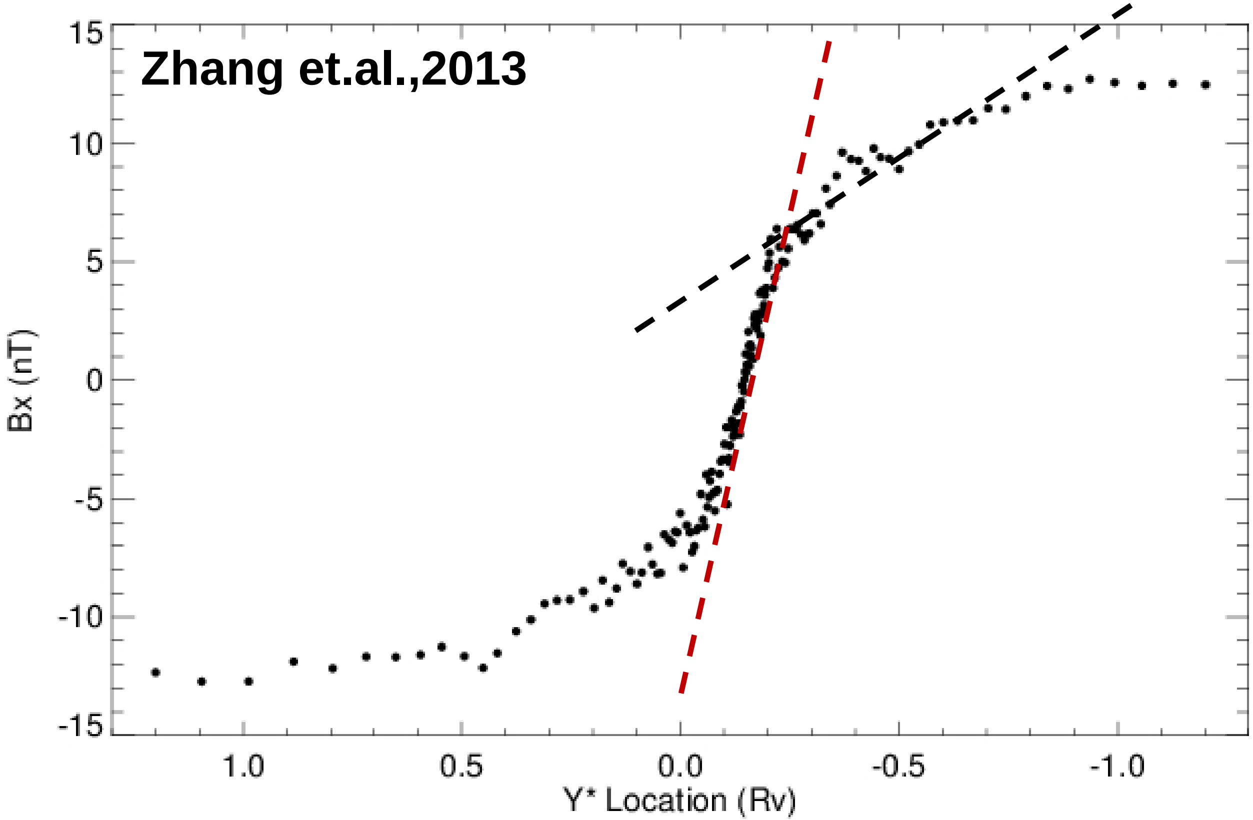
ACCRETION TYPE OF TAIL

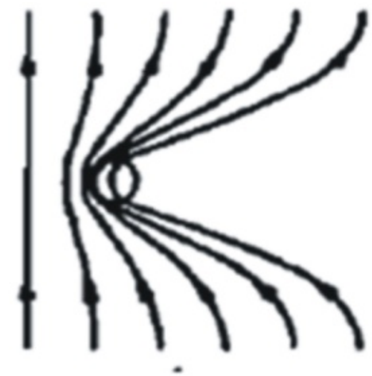
*COLLECTING MATERIAL*

(Вайсберг, Зеленый, 1982)

(VEX DATA , x=-3 $R_V$)

AVERAGE TRANSVERSE PROFILE OF B



DOUBLE SCALE SRUCTURE (~50%)

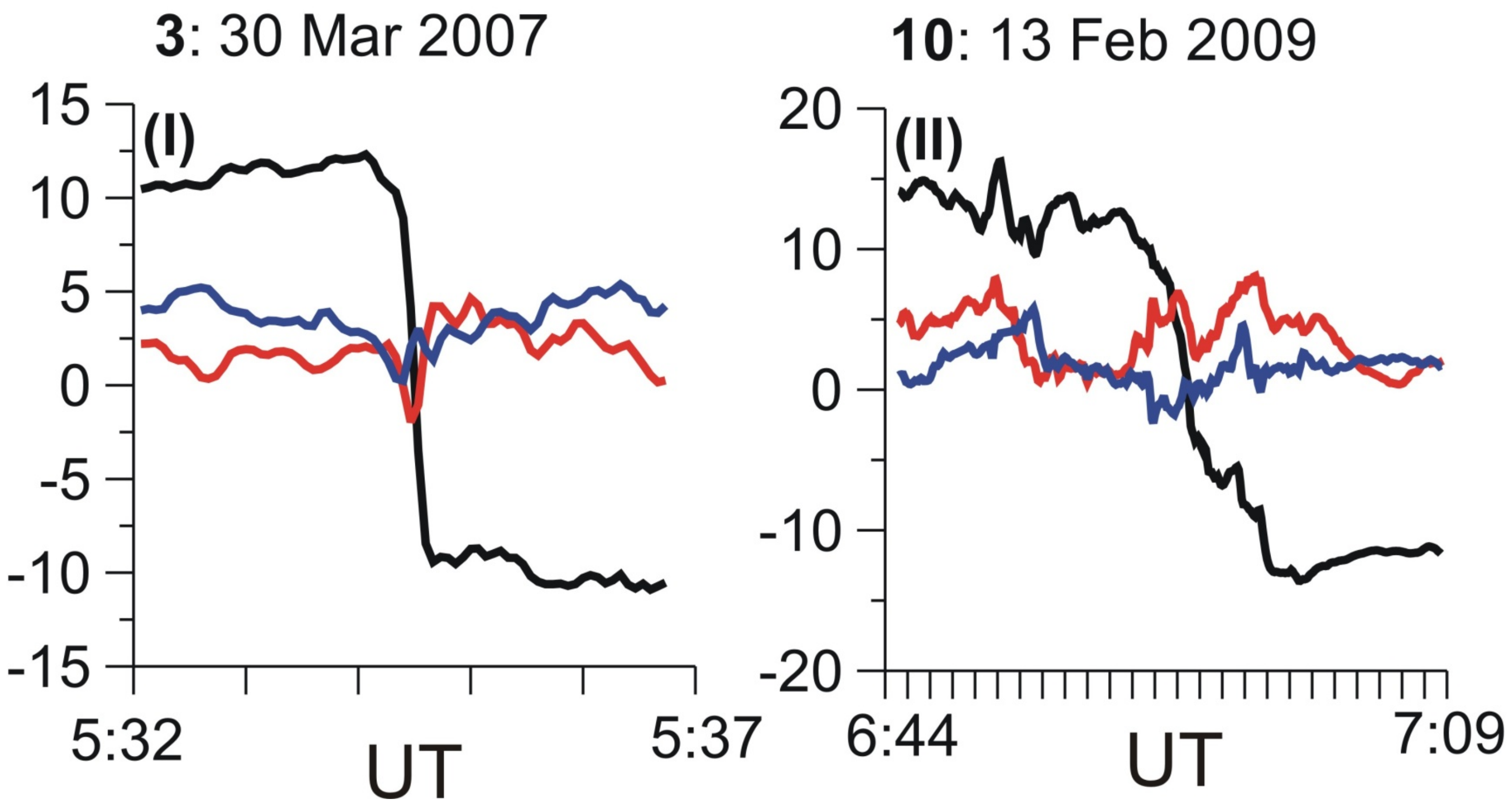
INNER SCALE

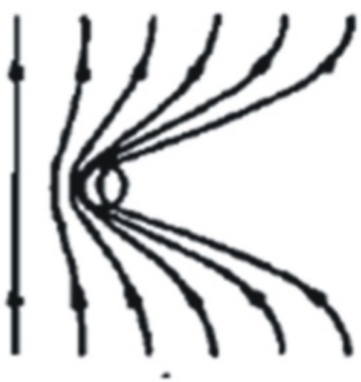
0.1 $R_V$

OUTER SCALE

0.4 $R_V$

# VEX EXAMPLES OF CS CROSSINGS



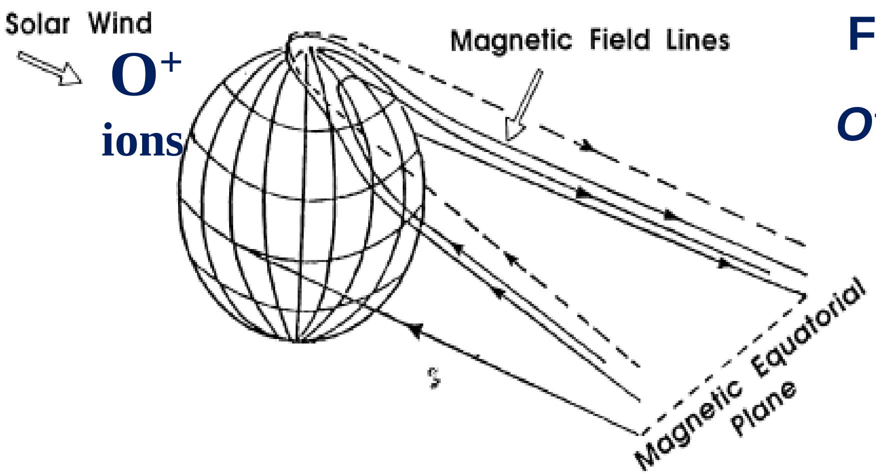
**LOCAL COORDINATE SYSTEM** $(\mathbf{l}, \mathbf{m}, \mathbf{n})$

**NEUTRAL PLANE** $B_l = 0$

**AVERAGED NORMAL FIELD** $B_{n,m} \sim 0.1 B_0$

$B_0$ **- поле $B_l$ на границе токового слоя**

# DOUBLE SCALE STRUCTURE



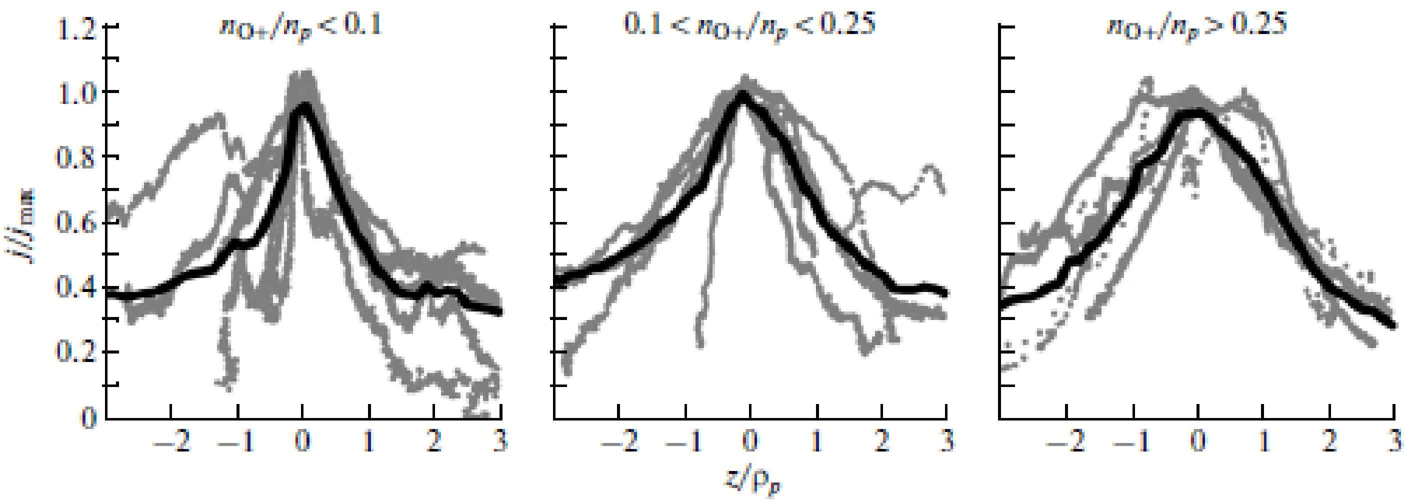

**FEW ION POPULATIONS IN PLASMA SHEET**

***$O^+$ proportion depends on the effectivity of the pick up process at the day side***

**Single scale CS**
**PROTON CURRENTS**

**45% / 55%**

**DOUBLE SCALE CS**
**Both $H^+$ and $O^+$ currents**

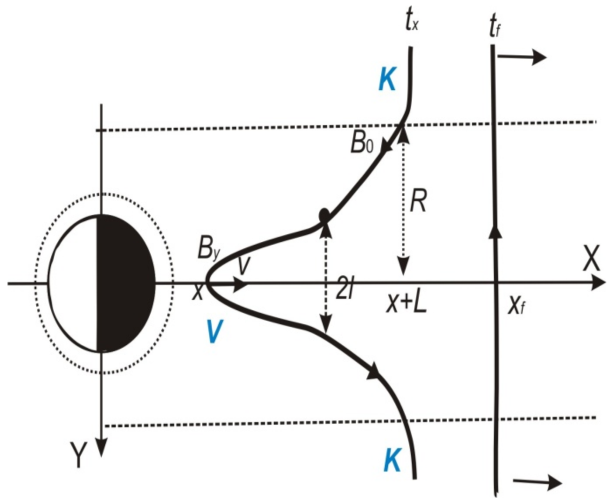



**ZELENYI / VASKO, 2011**

# ESTIMATES OF THE LENGTH OF THE ACCRETION TAIL

$$\frac{1}{v_A^2(x_0)v(x_0)}\left(\frac{L^2 l}{R}\right)\frac{\partial v}{\partial x}=\frac{L}{v^2}-\frac{l}{2R}\frac{\partial}{\partial x}\left(\frac{L^2}{v^2}\right)$$

$$L(x)=L(x_0)+\int_{x_0}^{x}\left(v_{sw}/v-1\right)dx$$




PVO data at $x=12\,R_V$

**Thin current sheet**

$$\boxed{l=0.25\,R_V}$$

**THICK CURRENT SHEET**

$$\boxed{l=R=2.5\,R_V}$$

**IN THE POINT OF THE STRAIGHTENING OF FL**

$$L(x_f)=0 \qquad v(x_f)>v_{sw}$$

**TIME OF STRENGTHENING**

$$\Delta t=(x_f-x_0-L(x_0))/v_{sw}$$

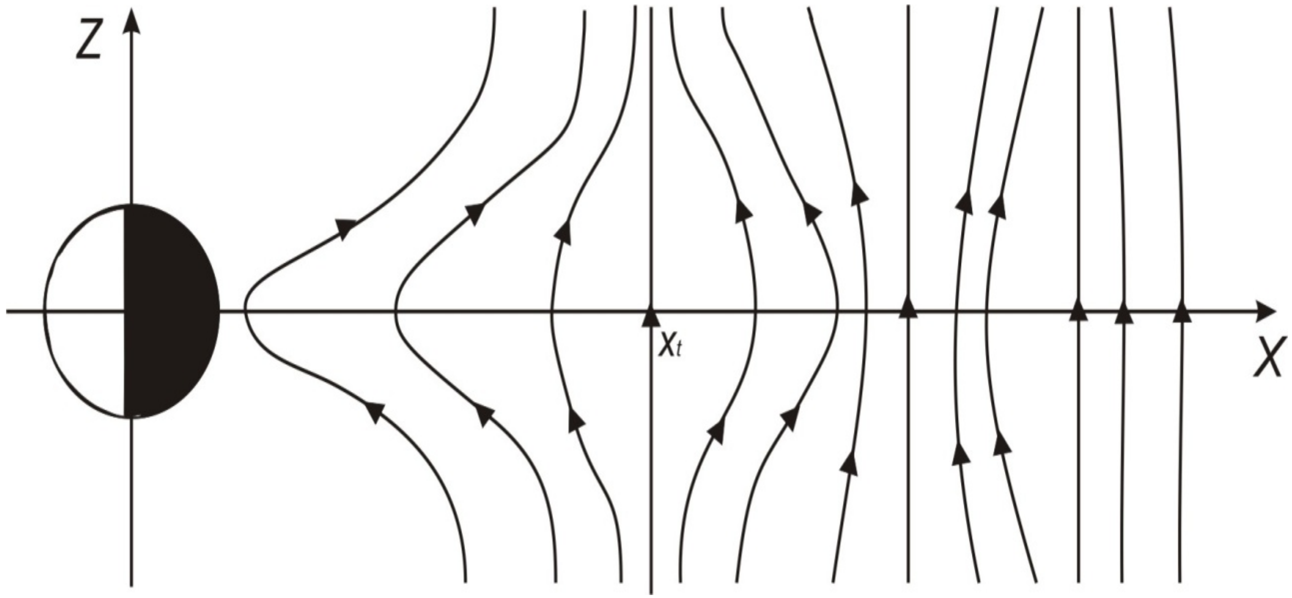
$x_f \sim 31\,R_V$

$v_f \sim 920$ км/с, $\Delta t \sim 160$ с

$x_f \sim 44\,R_V$

$v_f \sim 620$ км/с, $\Delta t \sim 360$ с

# ENTIRE TAIL LENGH



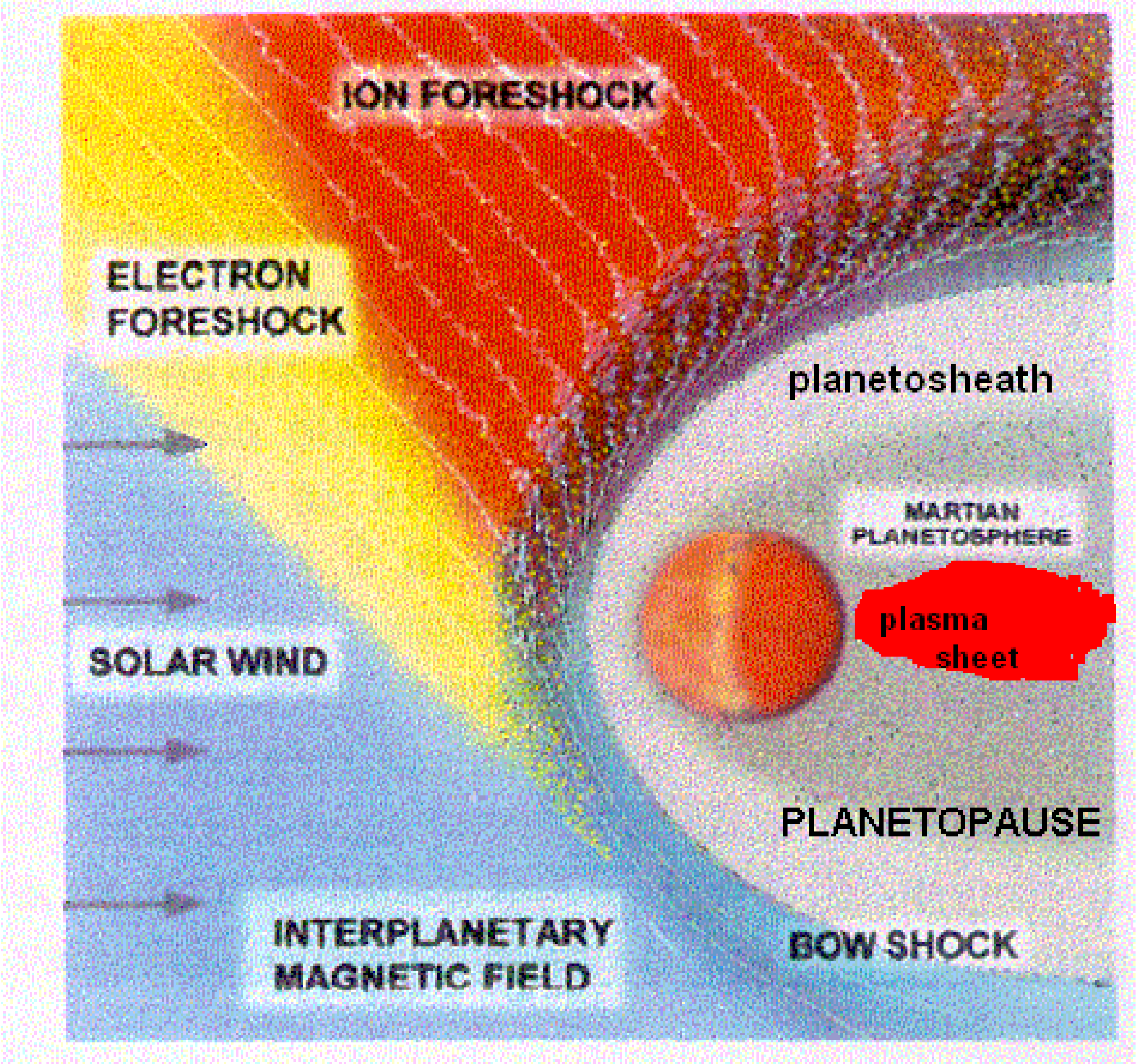

$x_t \sim 40\,R_V$ - **TAIL LENGTH = OSCILLATING WAKE**

$\Delta t \sim 600\,c$ - **TIME OF DRAPING**

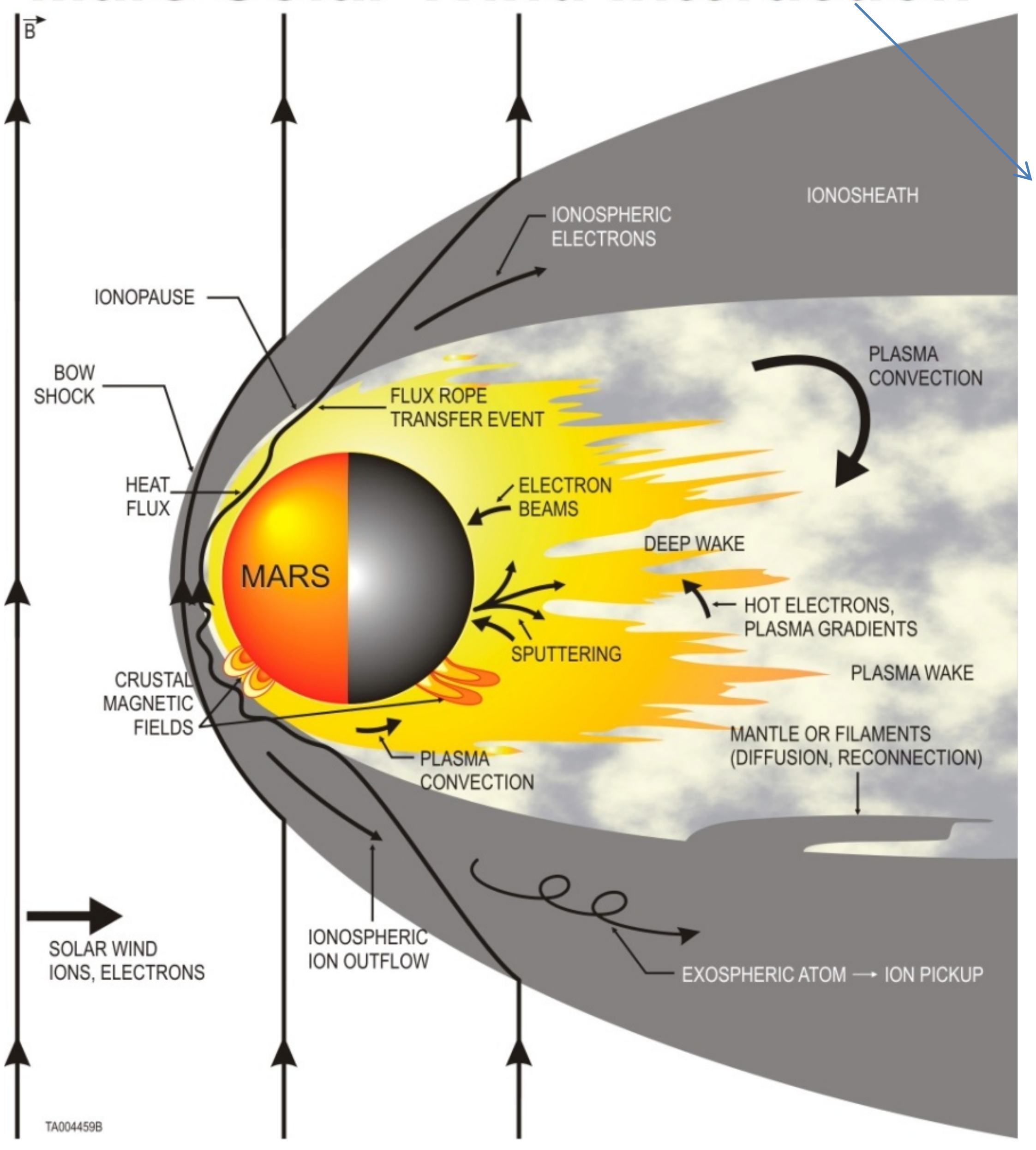
$v_f \sim 640\ \text{км}/c$ - **VELOCITY AT THE $X_l$ POINT**

VASKO, 2016

# MARS –"COMBINED" MAGNETOSPHERE



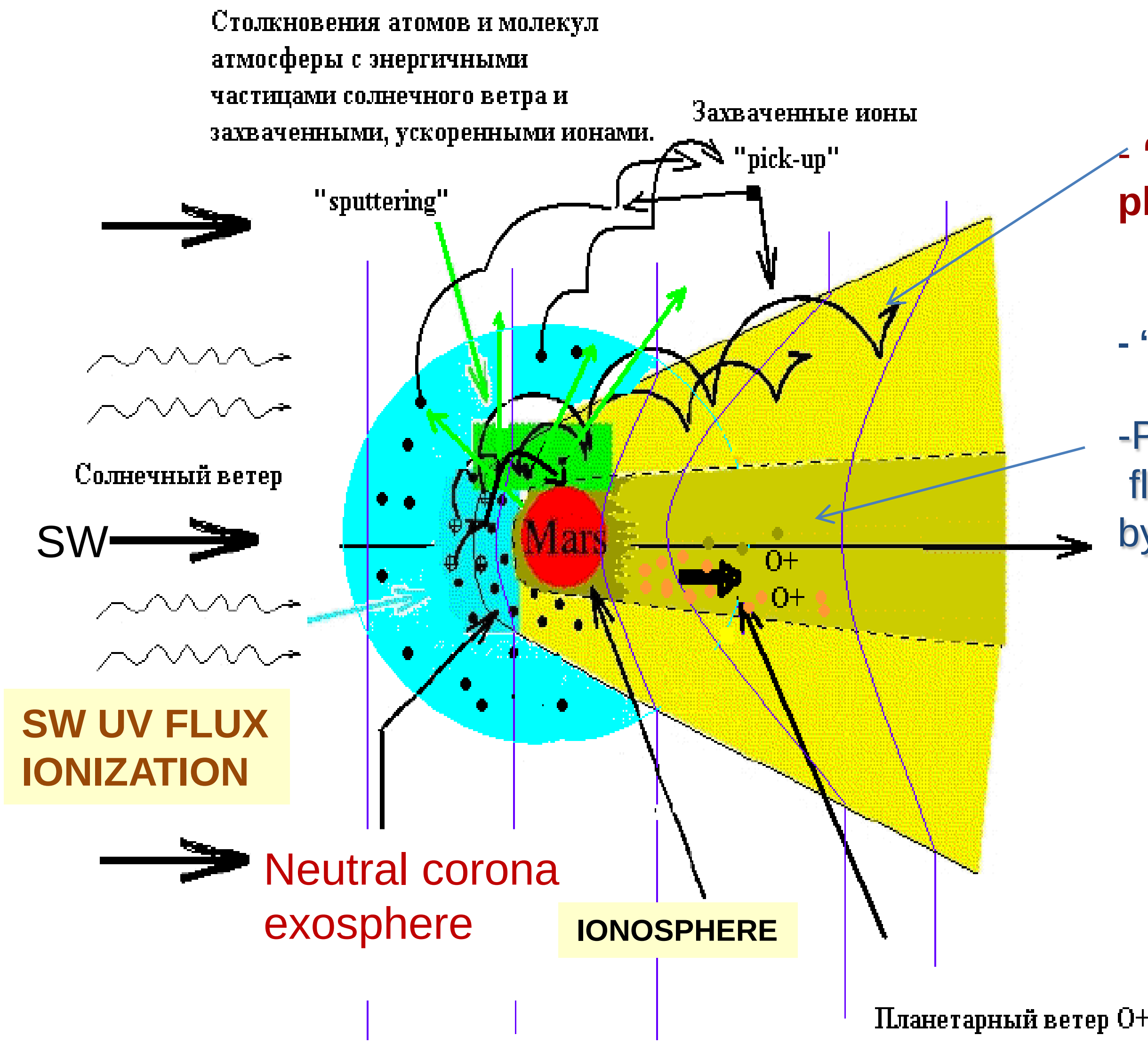
# Mars Solar Wind Interaction




→ **COMETARY FEATURES**

- **Solar Wind Interaction with an ionosphere and low gravity planet**
- **SW – Mini-Magnetosphere – Ionosphere Coupling (incl. Reconnection, Cusp Formation & Field-Aligned Current Generation)**
- **Atmospheric Loss – Ion Pickup, Ionospheric Clouds & Streamers, and Auroral-type Processes**

# MARS -NONTHERMAL ATMOSPHERIC DISSIPATION




**-Dissociative recombination**

**$O_2^+ + e \rightarrow O^* + O^* + dE$**

**- “pick-up”of ionized planetary ions by SW flow**

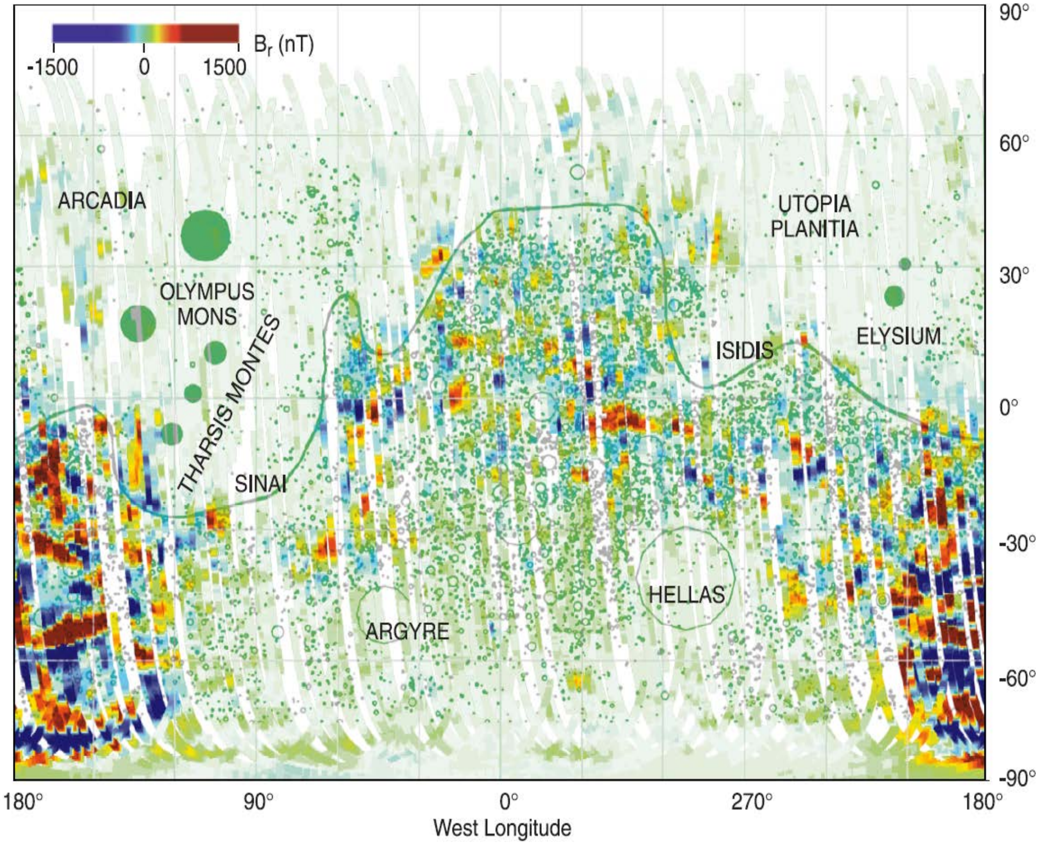
**- “sputtering”**

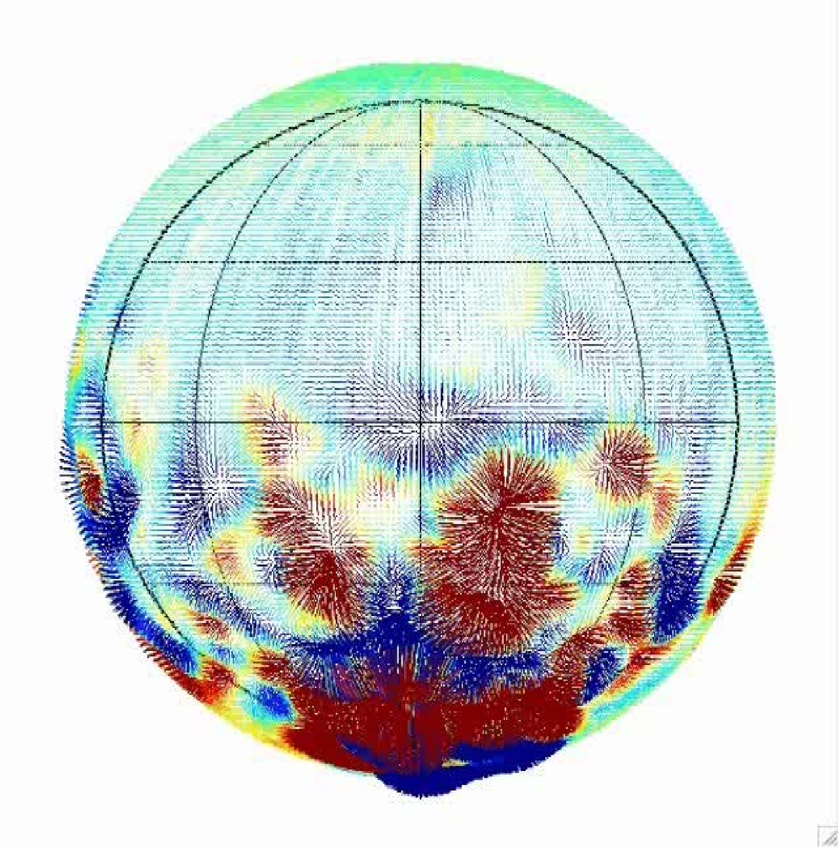
-PLANETARY WIND O+

flow of planetary ions trapped by Solar wind

# MARTIAN "MAGNETOSPHERE"

## Mars Global Surveyor – inhomogeneous magneization of a crust



**Distribution of radial component of Martian magnetic field at ~ 200 km height**

**Crustal Magnetic field at 400 km**

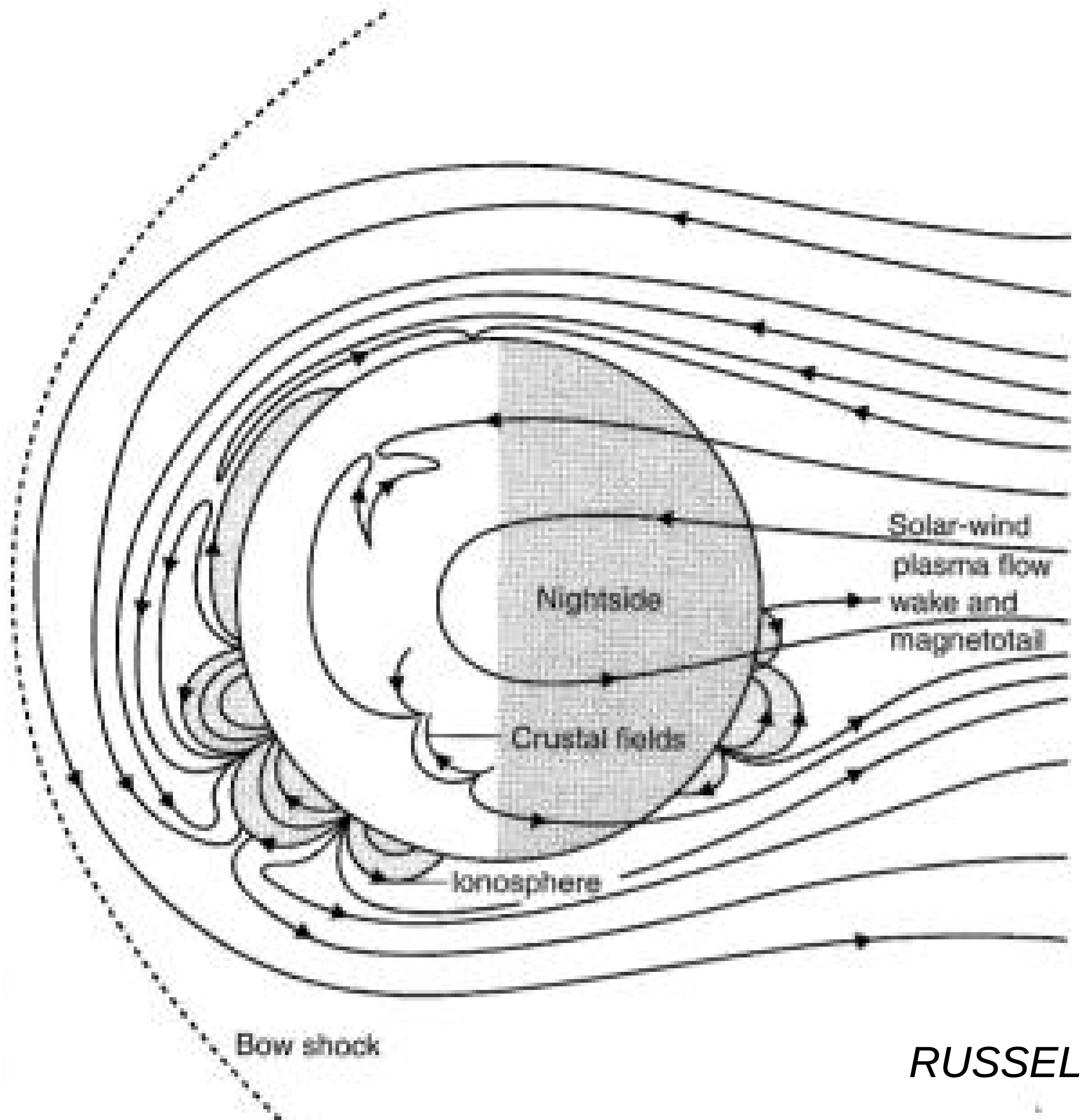
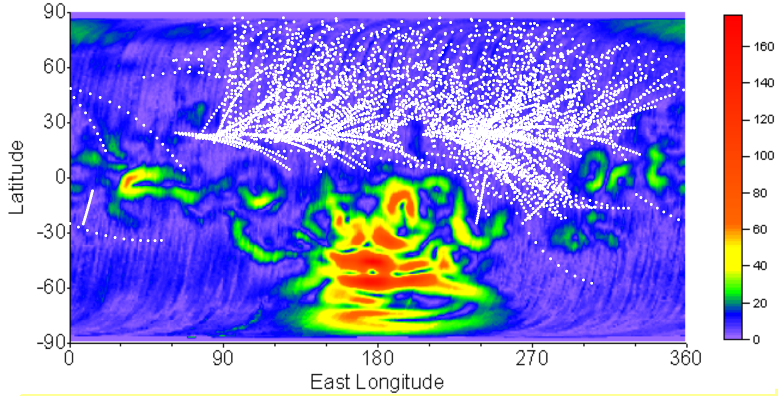



FIGURE 8.18. Illustration of the solar-wind plasma interaction with Mars, where both an ionosphere and remanent crustal magnetic fields define the obstacle. The plasma interaction includes the induced aspects of the Venus interaction, but also has the equivalent of "mini-magnetospheres". The crustal fields can merge or reconnect with the draped interplanetary field where they have antiparallel components – just as for a planetary magnetosphere. This produces regions of magnetically "open" and "closed" fields in the obstacle boundary, and also in the magnetotail in the solar-wind wake. Lunar remanent fields interact with the solar-wind fields in a similar way, but are not additionally affected by induced fields in an ionosphere.

*RUSSELL AND LUHMANN , 2017*

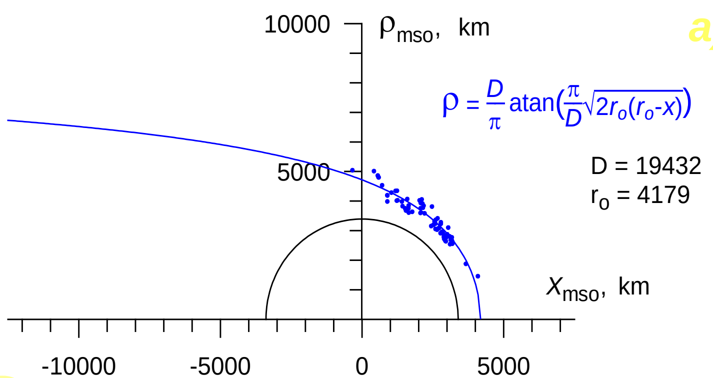
# Mars Global Surveyor – influence of local crust magnetization at position of martian magnetopause

All $\rho V^2$, $B_{hor}$(400km) < 10 nT beneath MPb streamline

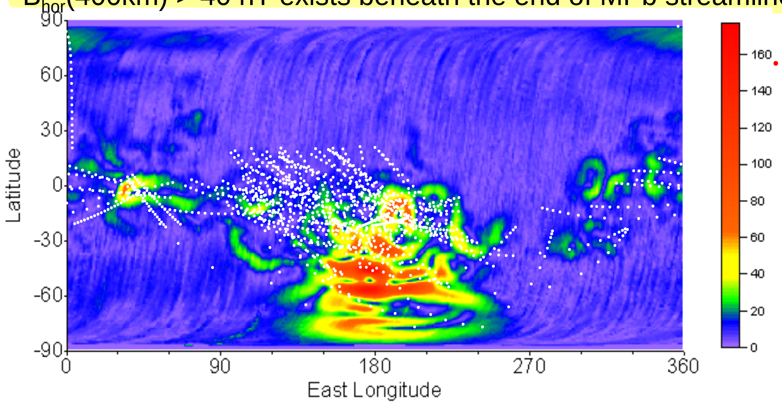



0.5 < $\rho V^2$ < 1.4 nP

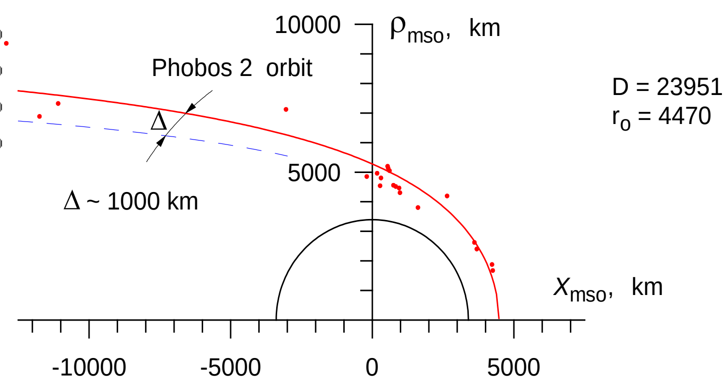
*a) Usual flow lines*




$B_{hor}$(400km) > 40 nT exists beneath the end of MPb streamline




*б) Flow line above local B enhancement*

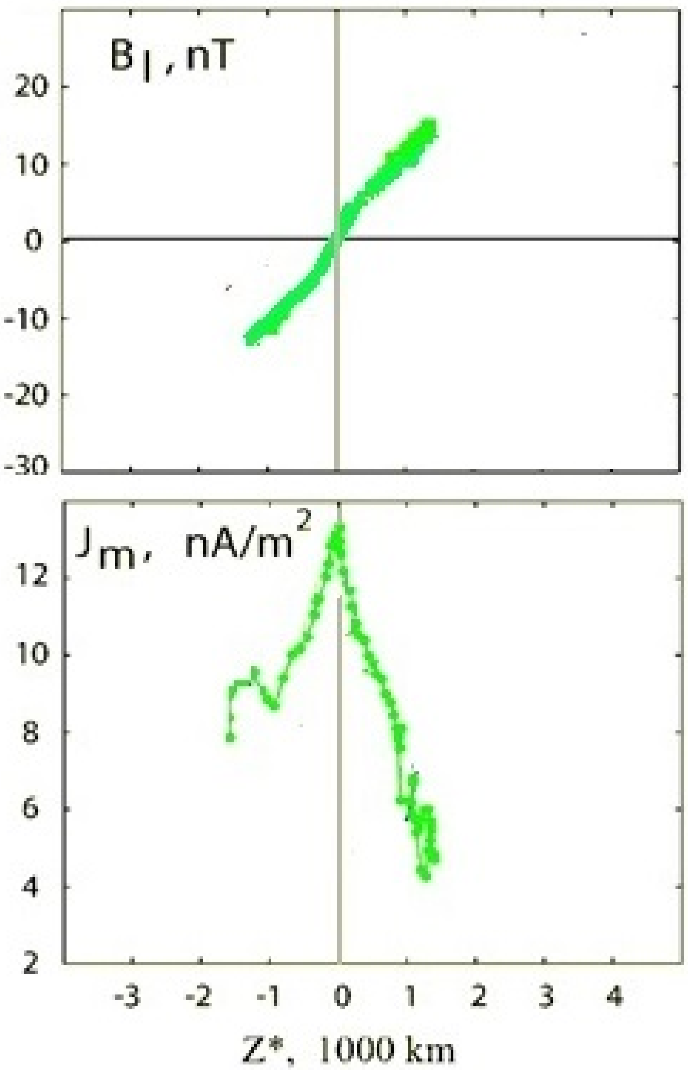



**LOCAL CRUST MAGNEIZATION INCREASES THE HEIGHT OF THE DAY SIDE MAGNETOPAUSE FOR A FEW HUNDREDS KILOMETERS**

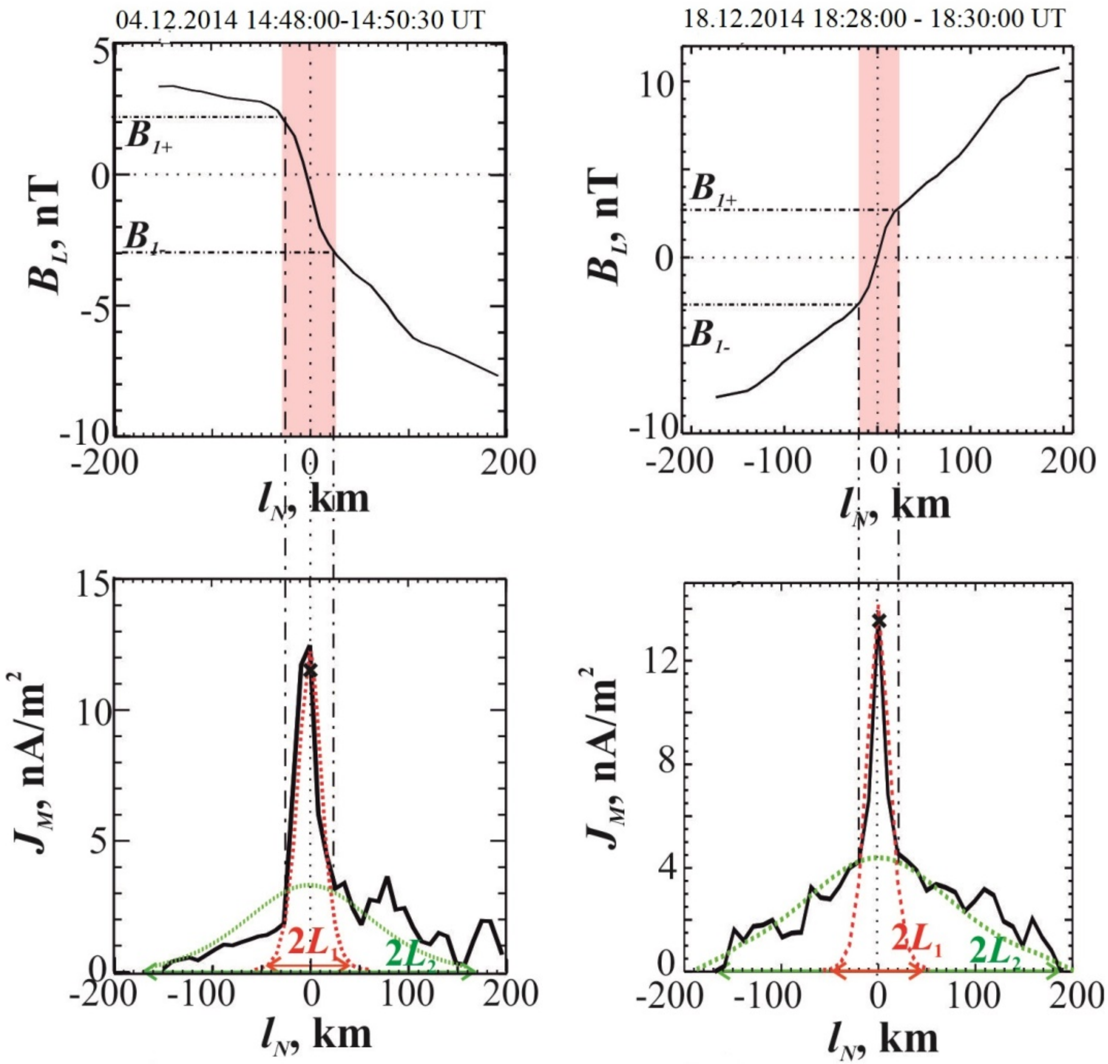
*VERIGIN*

# Multiscale current sheets in the Earth and Martian tails

Earth magnetotail
CLUSTER observations




Martian magnetotail
MAVEN observations




For details see poster by Grigorenko et al.

## ANOTHER TYPE OF MAGNETOSPHERES -

### "MADE OF INTERPLANETARY MAGNETIC FIELD LINES"

| PLANET | MAGNETIC FIELD | | IONOSPHERE |
|---|---|---|---|
| MERCURY | + | | - |
| VENUS | - | | + |
| EARTH | + | | + |
| MARS | + | - | + |

## COMETS MARS VENUS

*DIFFERENCES: SIZE OF PLANETARY NEUTRAL CORONA DETERMINES THE EFFECTIVITY OF THE "PICK UP" PROCESSES AND TYPE OF INTERACTION*

*SLOW DECELERATION DUE TO "PICK UP" (COMETS, SOMETIMES MARS & SHOCK TYPE DECELERATIOIN FOR VENUS AND OFTEN MARS*

*Pecularities of Interaction due to crustal magnetic field (local auroras)*

*UNIVERSAL "LONG" MAGNETOTAILS WITH THIN CURRENT SHEETS*

*RECONNECTION AND TAIL DISCONNECTIONS ??*

- **Nonlinear physics**
- ***Shocks***
- ***Wave particle interactions***
- *often strong turbulence*
- *Soliton like structures*

*new instabilities due to mass loading*

- ***Reconnection***
- *localized (patchy)*
- *+ dynamic*
- ***Very thin current sheets***

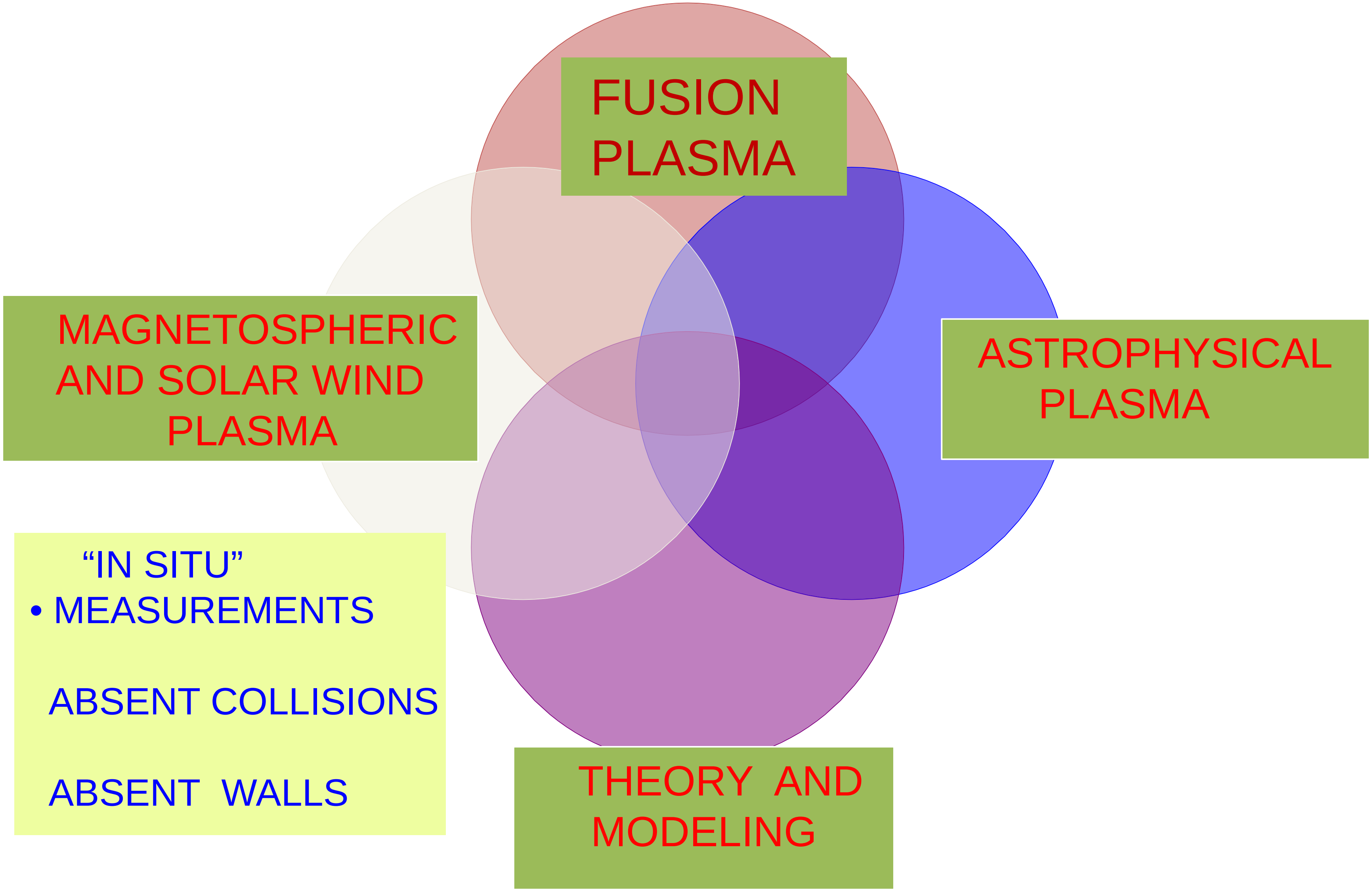
*(sub ion scales)*

*Often Nonadiabatic Ions*

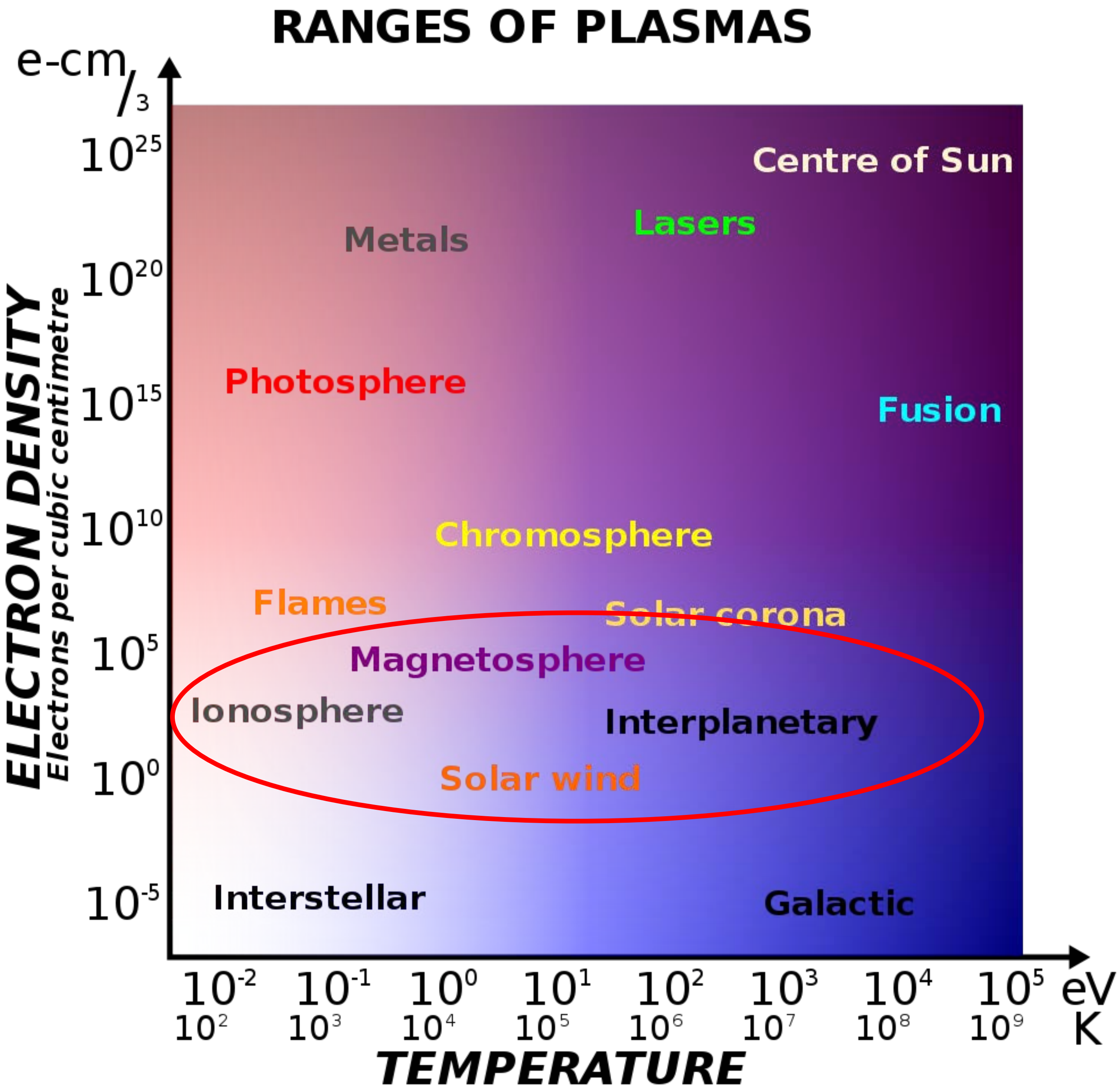
*Sometimes also electrons*

- ***Filamentation and structuring***

# Plasmas in Astrophysics and in the Laboratory:



BIG PICTURE


RANGES OF PLASMAS
e-cm/3
ELECTRON DENSITY
Electrons per cubic centimetre
10^25
10^20
10^15
10^10
10^5
10^0
10^-5
Centre of Sun
Lasers
Metals
Photosphere
Fusion
Chromosphere
Flames
Solar corona
Magnetosphere
Ionosphere
Interplanetary
Solar wind
Interstellar
Galactic
10^-2 10^-1 10^0 10^1 10^2 10^3 10^4 10^5 eV
10^2 10^3 10^4 10^5 10^6 10^7 10^8 10^9 K
TEMPERATURE