Mars Global Surveyor and Mars Express and Preparation of MAVEN

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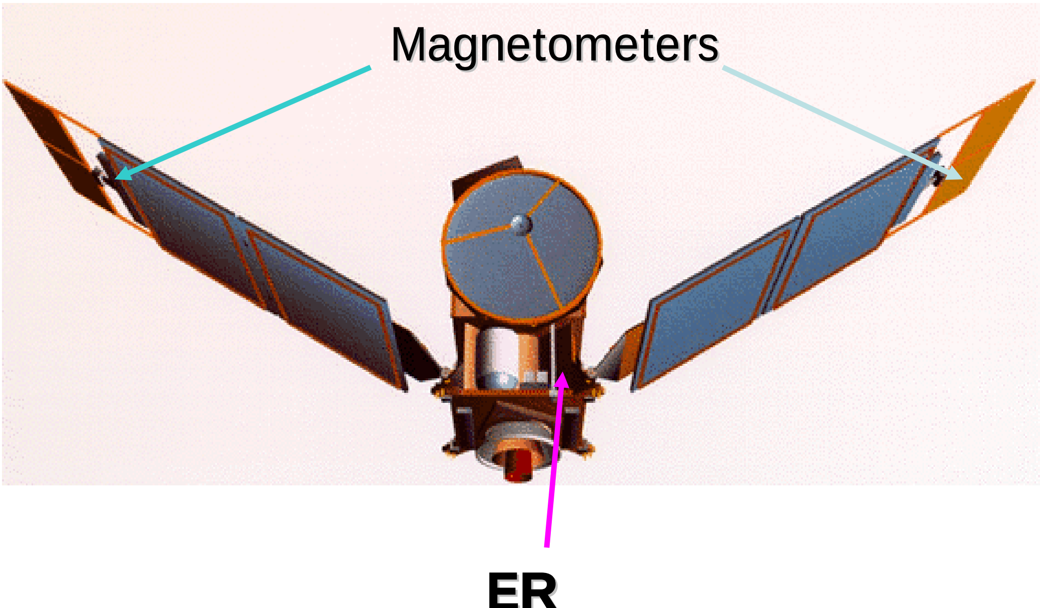
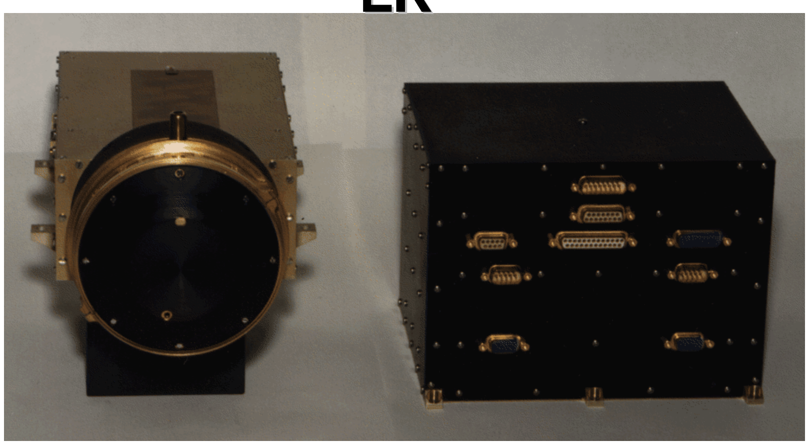
HELIOSARES Kick-off meeting, Paris, UPMC, October 5 – 6, 2009

Mars Global Surveyor
MAG/ER Experiment
P.I.: Mario Acuña (GSFC)





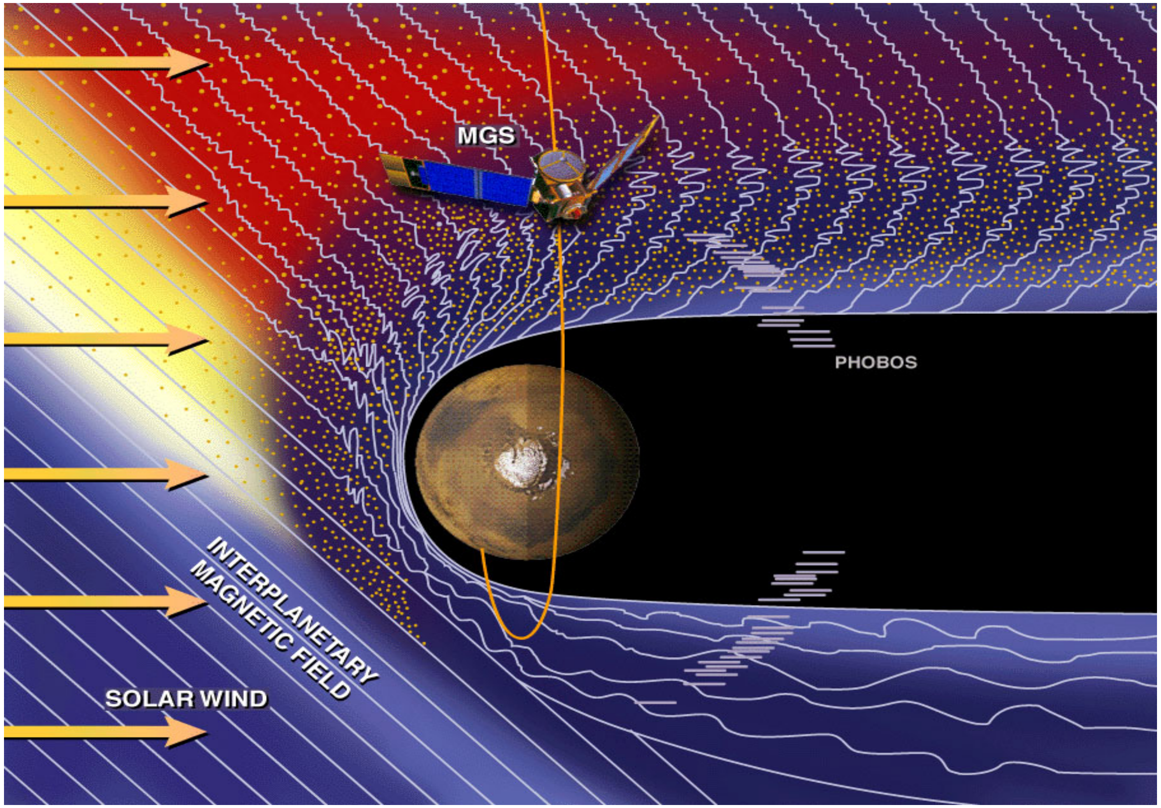
- **MAG: 2 tri-axial magnetometers (NASA GSFC)** (up to 32 vectors/sec).
- **ER: Electron spectrometer (SSL Berkeley - CESR)** measuring energy distribution from 10 eV to 20 keV (Fov: 360x14°,16 sectors of 22.5°; max. time resolution: 2 sec).
- **But no ion measurements!**

Data from 14/09/1997 to 03/11/2006

Mainly on PDS but not all

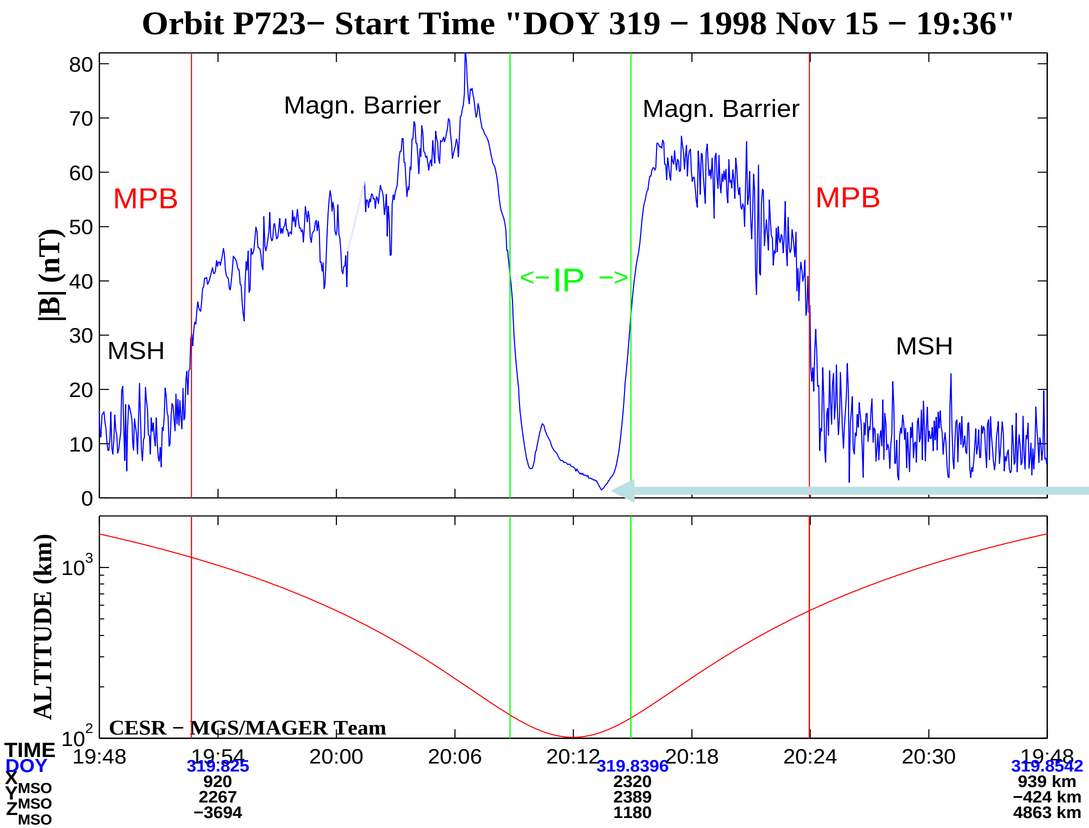
Solar Wind Interaction with MARS

Study of the electromagnetic coupling between a magnetized plasma wind supersonic and superalfvenic, and the neutral environment (through the ionization processes) of an object without macroscopic magnetic moment



MGS: lack of present dynamo at Mars

MGS: first spacecraft to reach low altitudes between 100 and 200 km
[Acuña et al., 1998]



[Mazelle et al., 2003]

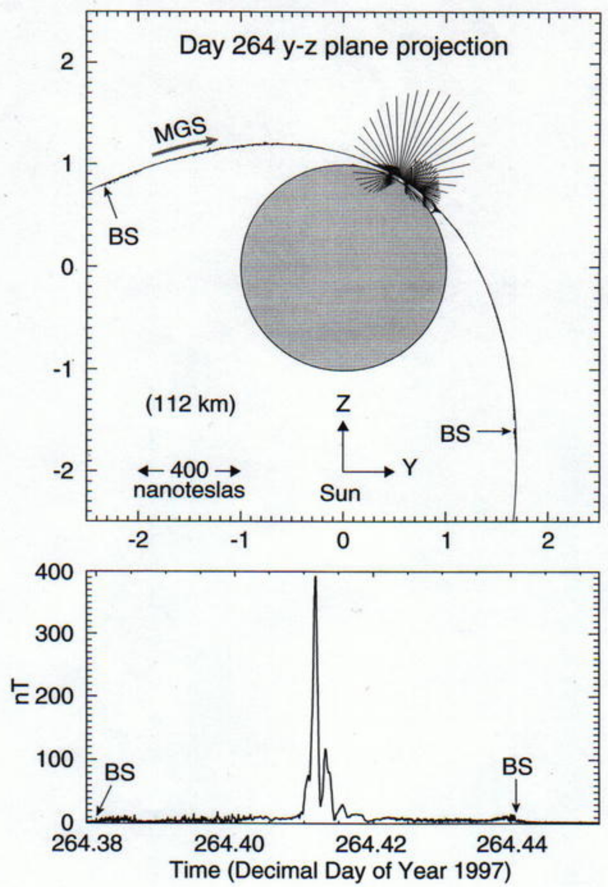
With an active planetary dynamo, the magnetic field strength should regularly increase with decreasing altitude and reach its maximum at periapsis.

Contrarily, |B| displays a minimum at periapsis sometimes nearly vanishes (close to instrumental accuracy).

→ **Mars has no active dynamo (no more)**

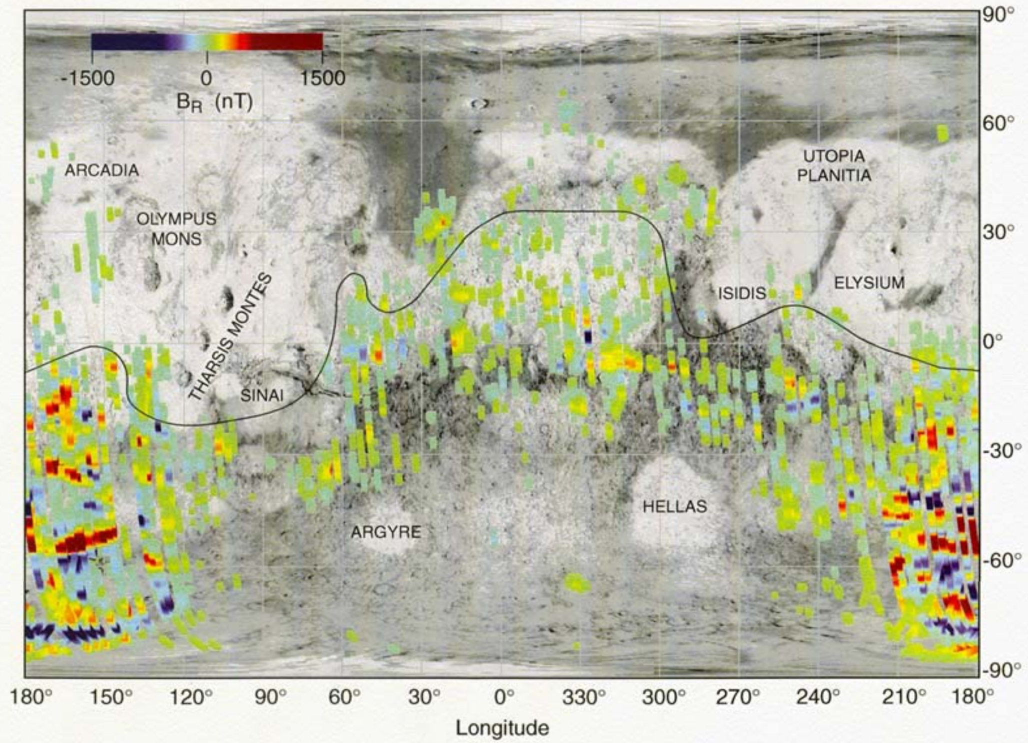
→ **Interaction with the solar wind of « atmospheric » type**

MGS: discovery of remnant crustal magnetism (paleomagnetism)



[Acuña *et al*., Science, 1998]

Map of crustal sources

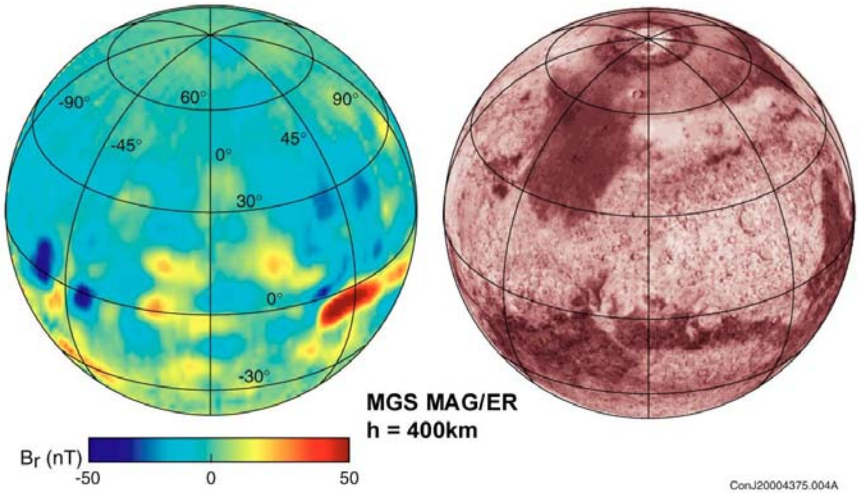


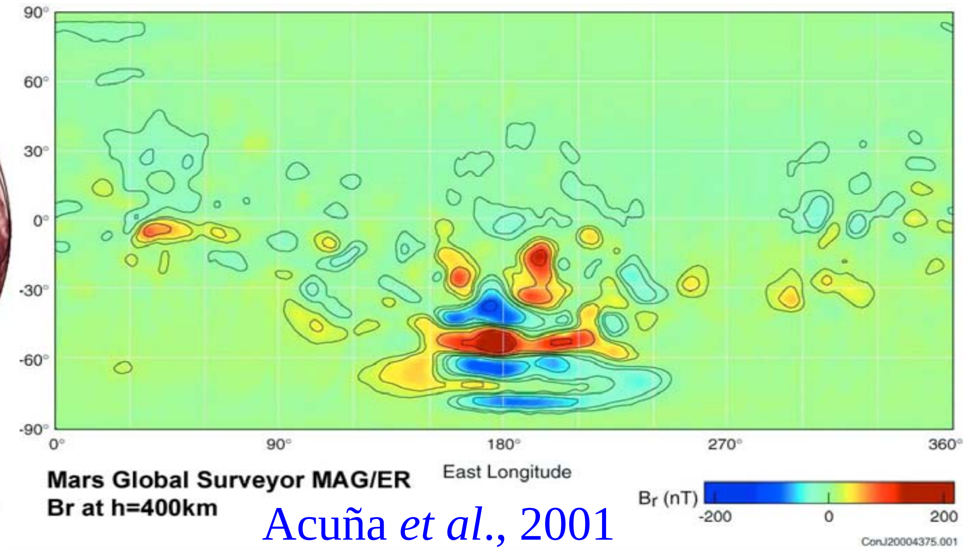
[Acuña *et al*., Science, 1999]

No source in old impact basins Hellas & Argyre

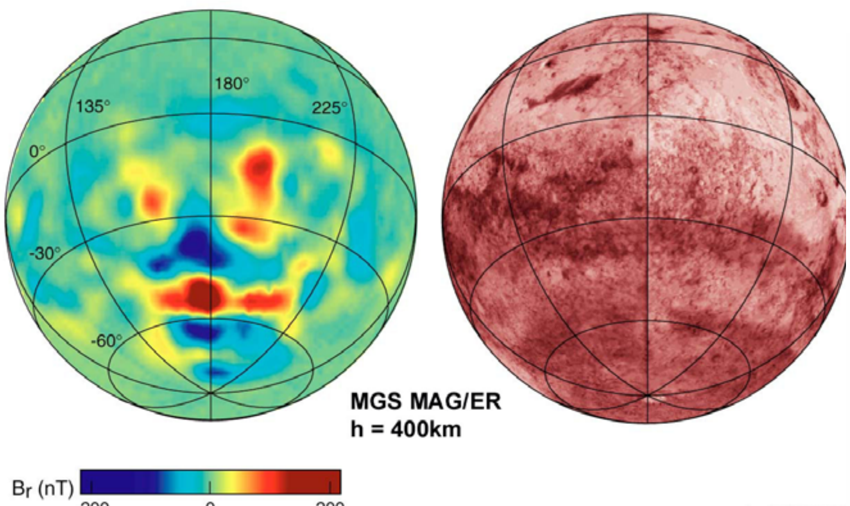
→ **dynamo ceased > ~3.9 10^9 years ago** → **atmospheric erosion by SW**

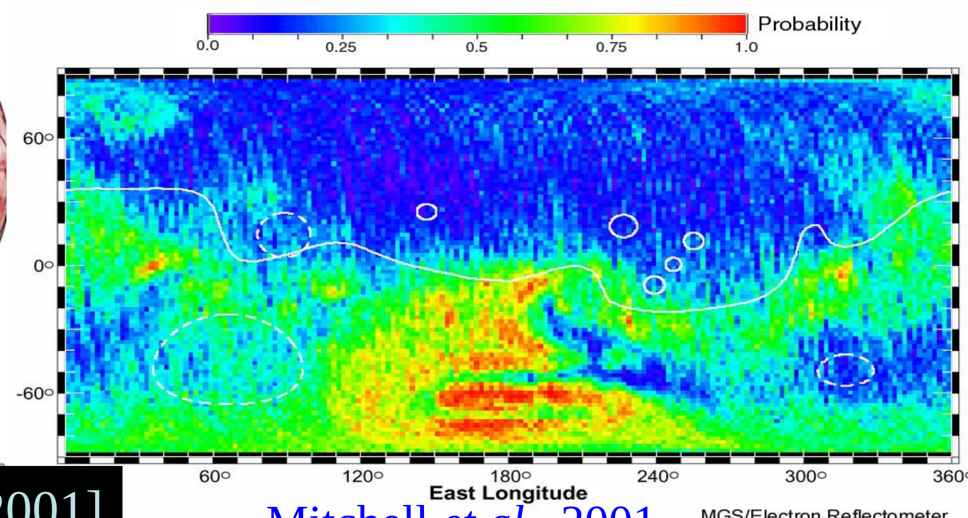
MGS: crustal magnetism observations from circular mapping orbit (400km)





Acuña *et al.*, 2001





Mitchell *et al.*, 2001

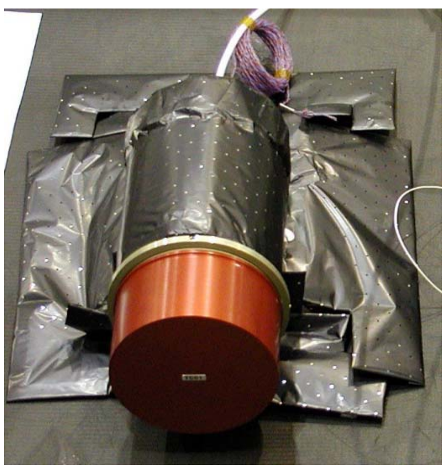
[*Journal of Geophys. Res.*, **106**, *E10*, 2001]

ASPERA-3 - Imaging plasma and energetic neutral atoms near Mars

PI: Rickard Lundin, Stanislav Barabash + ASPERA-team

Objective: To measure solar wind scavenging : The slow “invisible” escape of volatiles (atmosphere, hydrosphere) from Mars.

Question: Is the solar wind erosion the prime reason for the present lack of water on Mars?



Ion mass analyzer

Main Unit:

- Data processing
- Neutral particle imagers (NPI, NPD)
- Electron spectrometer (ELS)
- Mechanical scanner

Solar wind erosion of the martian atmosphere

Planetary wind = Outflow of atmosphere and ionosphere (cometary interaction)

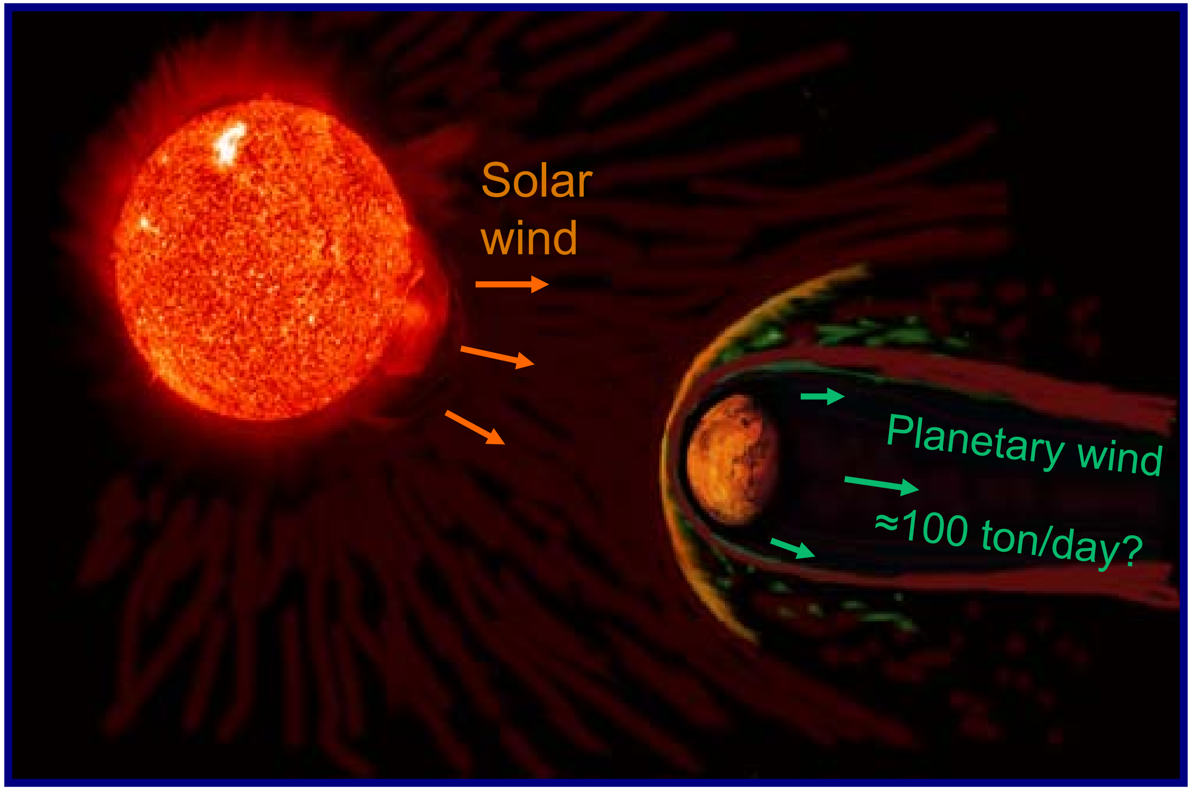
ASPERA doing global imaging and *in-situ* measurements of:

Inflow — solar wind

Outflow — planetary wind

using:

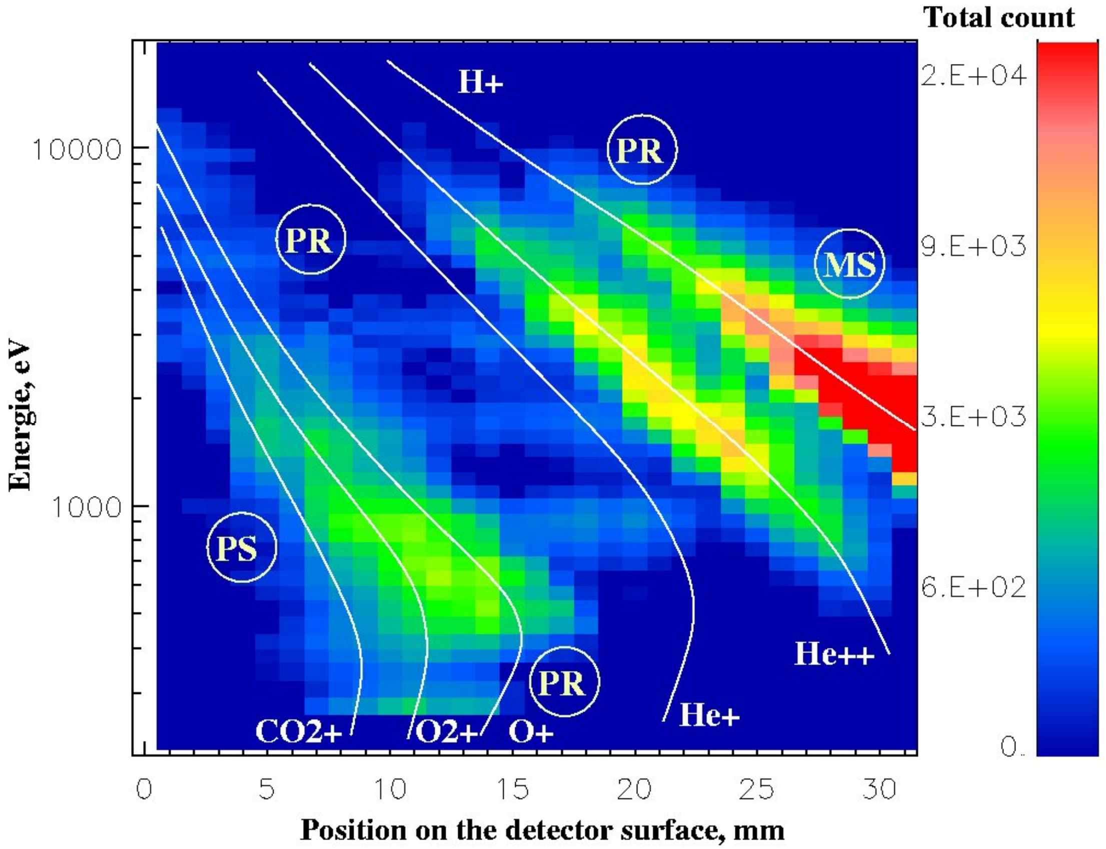
Energetic neutral atom cameras and plasma (ion+electron) spectrometers

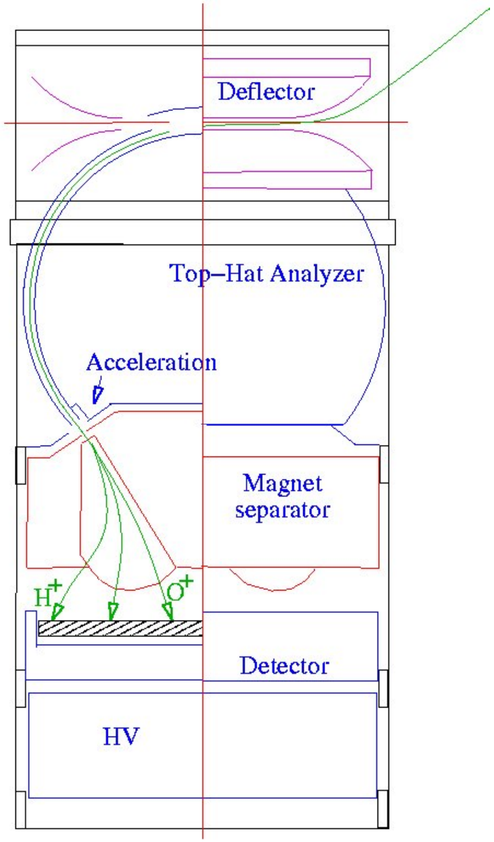


Note: Mars (and Venus) are planets lacking a strong intrinsic magnetic field (umbrella) => dehydration.

MEX Summary Mass-Energy plot

May 2004 – August 2006



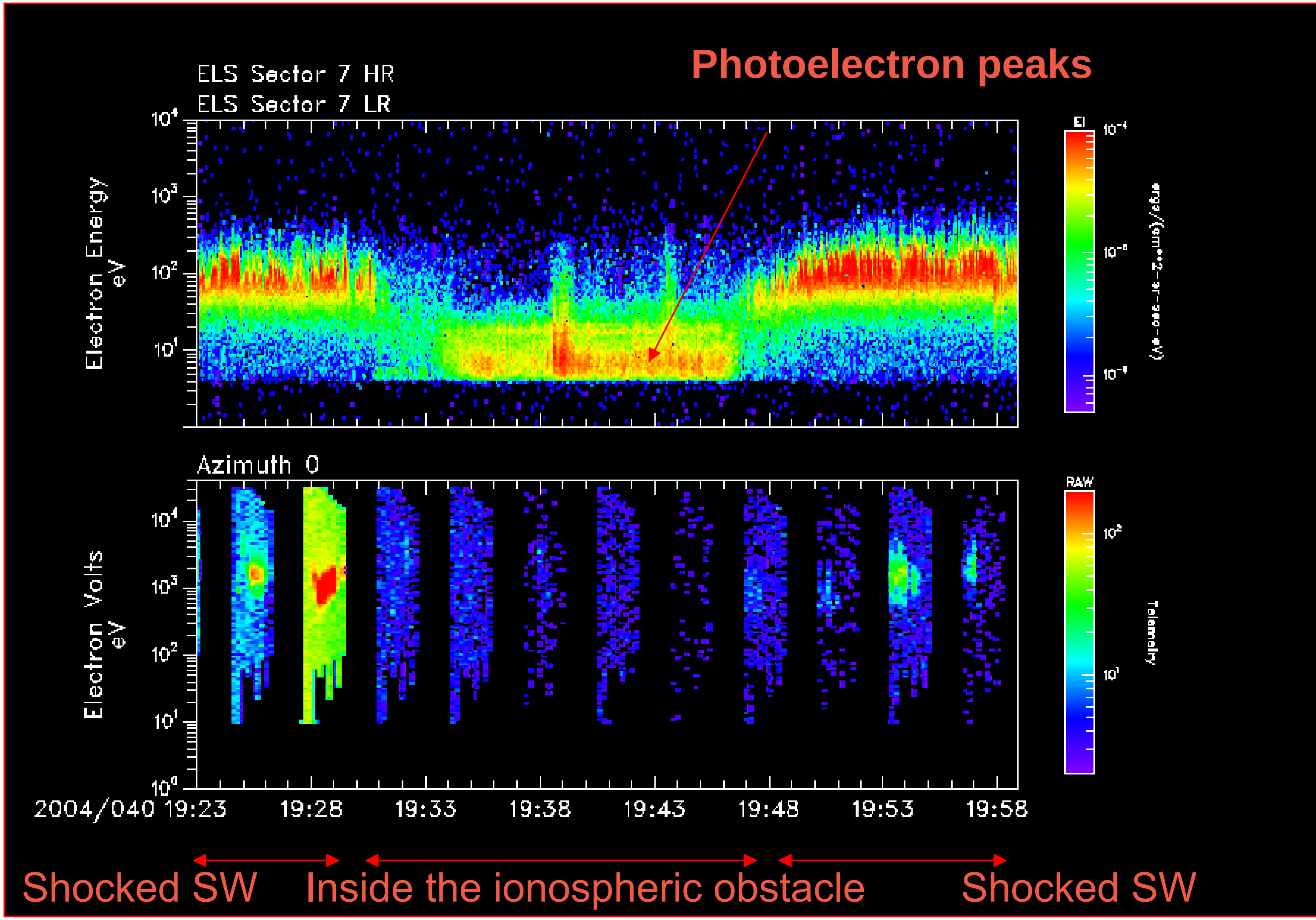


IMA-Mex could only see heavy ions **from 250 eV** to about 10 keV before april 2007 (new patch: possible from ~30 eV)

MEX encounter of the ionosphere at Mars

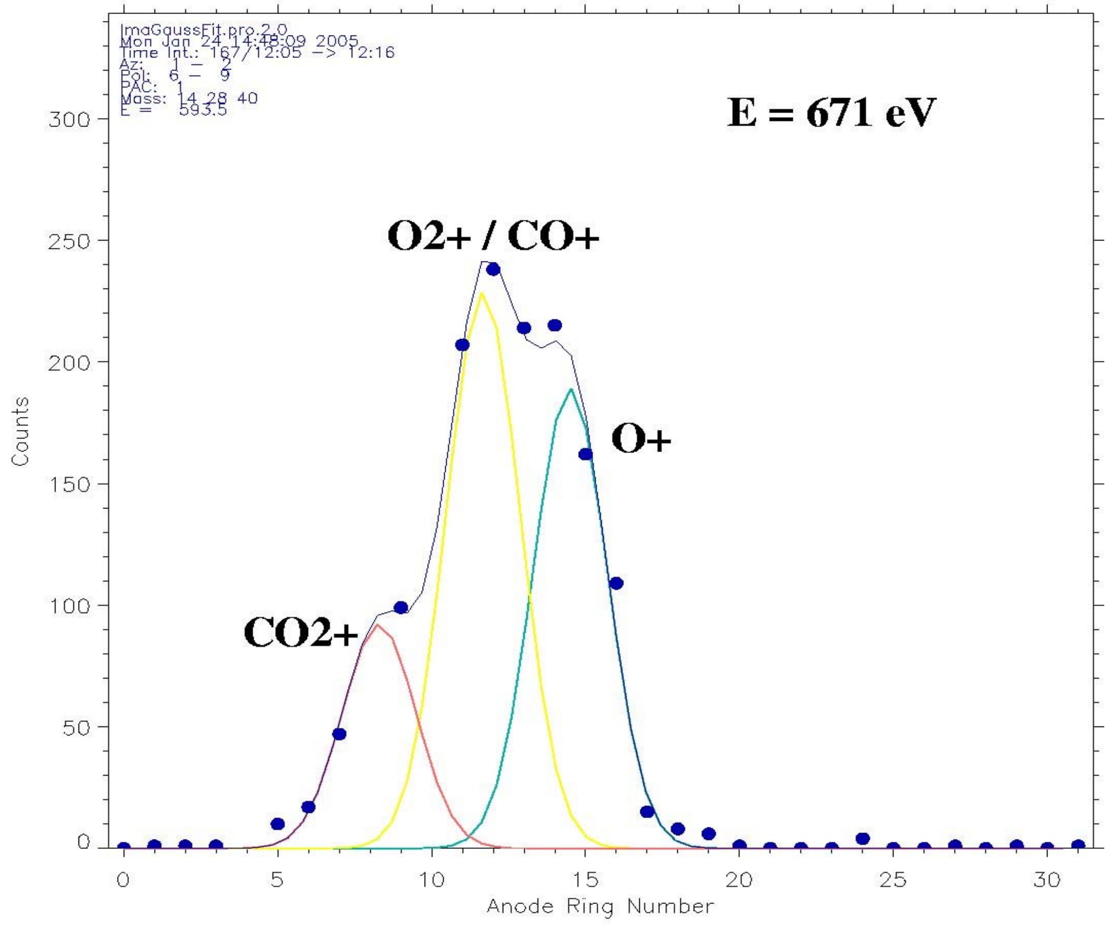
Electrons

Ions



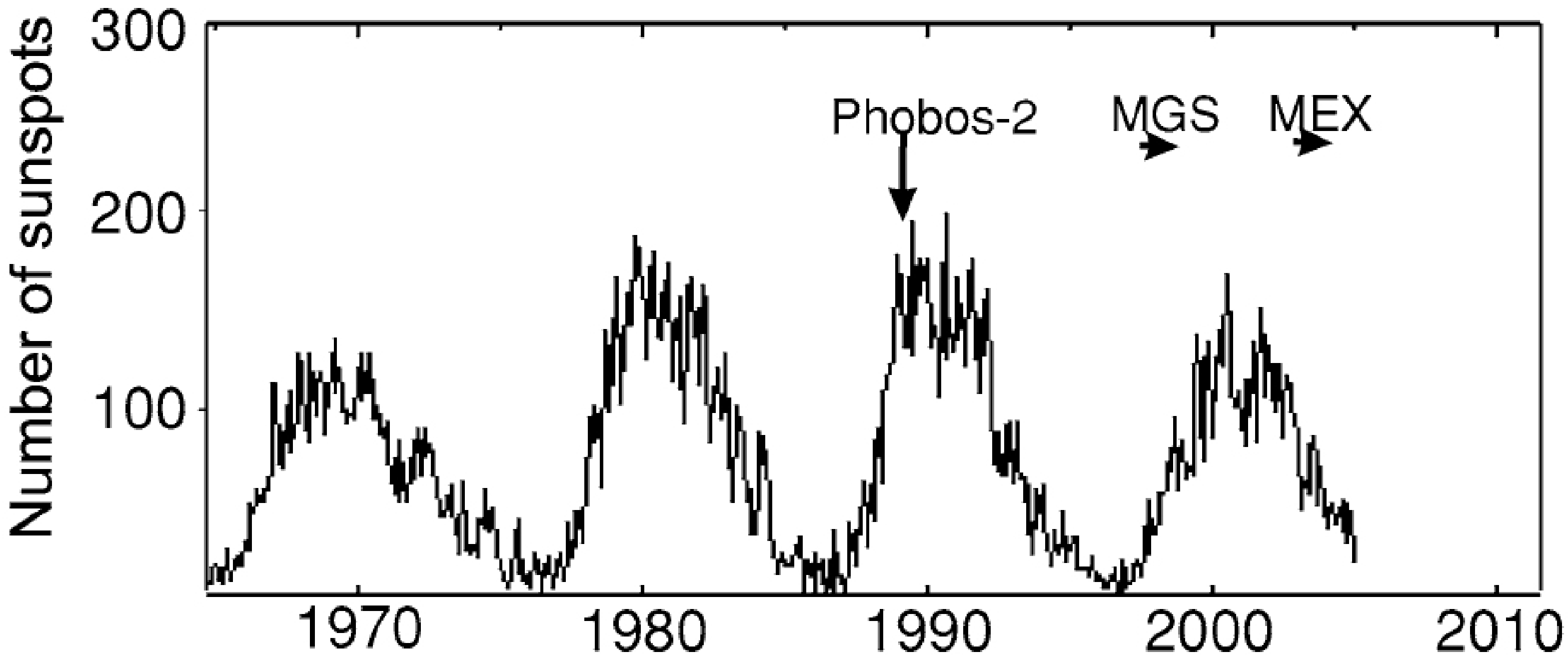
(for the first time!)

IMA one mass spectrum. Fitting of 3 species



We can resolve M/Q equal to 16, 32(28) and 44

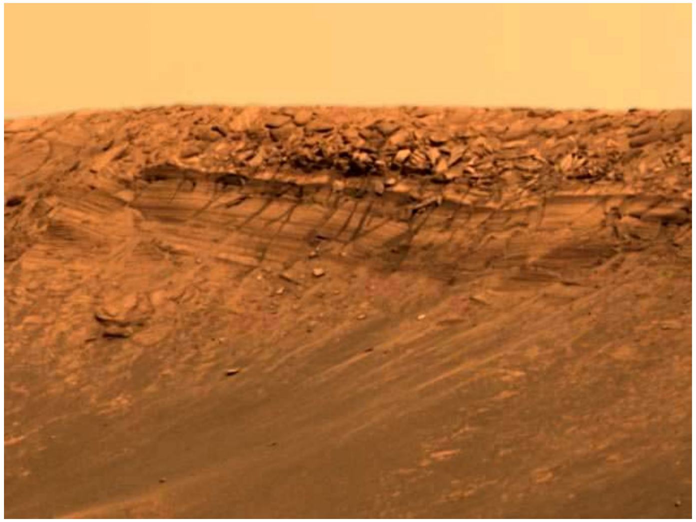
MGS and MEX: Solar Cycle



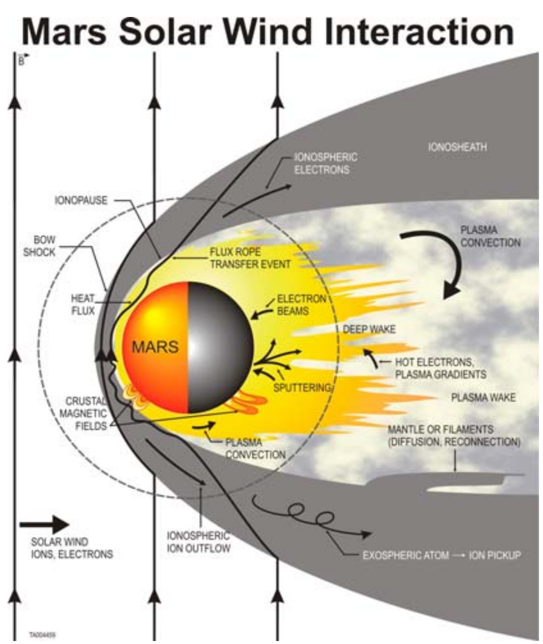
Available Data and tools

- All MGS data and MEX data available at CESR. More than at PDS!
- Expertise on instruments.
- Available specific data analysis software.

Science Rationale Behind MAVEN



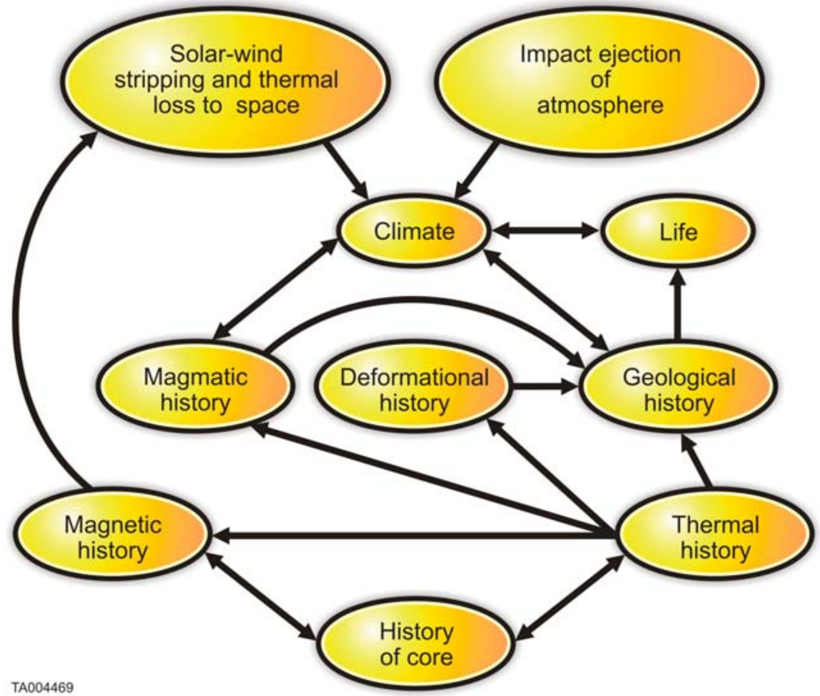
- The history of liquid water and of any greenhouse atmosphere determine the potential that Mars had throughout time to support life
- Loss of atmospheric CO_2, N_2, and H_2O to space has been an important mechanism for loss of the early atmosphere, and may have been the dominant mechanism.



- Only by understanding the role of escape to space through time will we be able to fully understand the history of the atmosphere, climate, and water, and thereby understand martian habitability.

MAVEN High-Level Science Questions

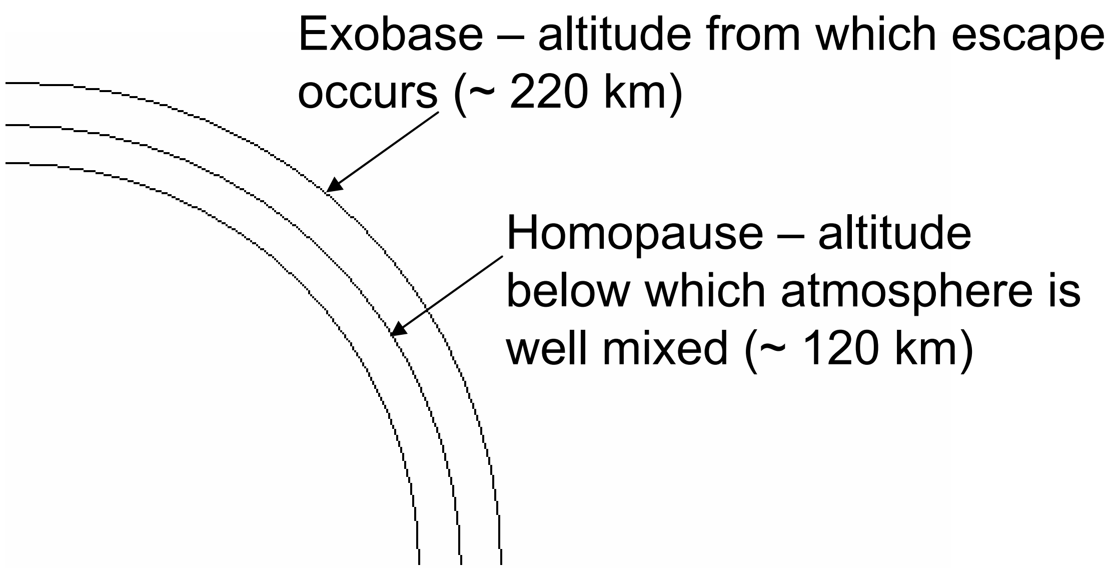
Major questions about Mars involve the history of its climate, the processes that control it, and the implications for martian habitability. Given the potentially important role that loss of gases from the upper atmosphere to space has played, we wish to address the following questions:



- What is the current state of the upper atmosphere, and what processes control it?
- What is the rate of escape of atmospheric gases to space at the present epoch and how does it relate to the underlying processes that control the upper atmosphere?
- What has the total loss of atmospheric gases to space been through time?

MAVEN Science and Measurement Objectives (1 of 3)

Science Objective	MAVEN Science Obj.	MAVEN Measurement Obj.
What is the current state of the upper atmosphere, and what processes control it?	Determine the current state of the upper atmosphere and its response to solar and solar-wind input	Measure the neutral composition between the homopause and the exobase
		Measure the composition and structure of the ionosphere between the homopause and the exobase
		Measure the composition and structure of the hot corona above the exobase
		Measure the solar and solar-wind input into the upper atmosphere

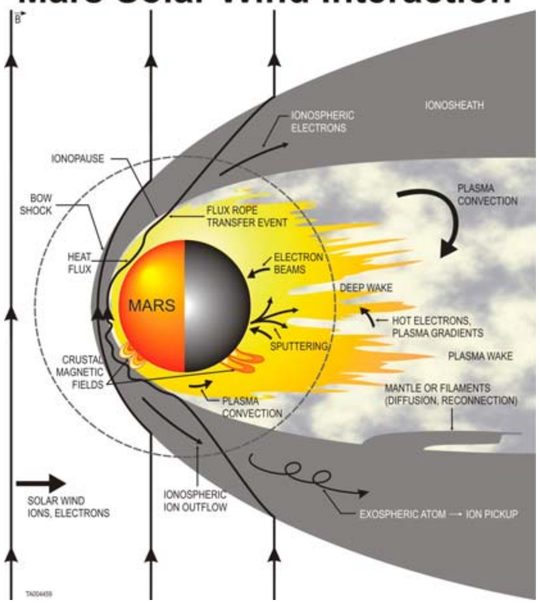


MAVEN Science and Measurement Objectives (2 of 3)

Science Objective

What is the escape rate at the present epoch and how does it relate to the underlying processes that control the upper atmosphere?

Mars Solar Wind Interaction



MAVEN Science Obj.

Determine the rate of escape via each of the important processes, or measure key parameters that allow us to infer the escape rates.

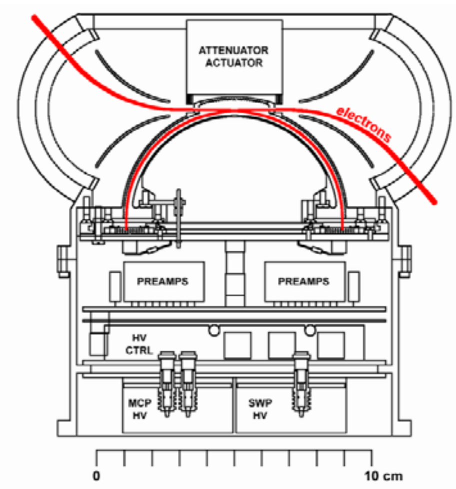
MAVEN Measurement Obj.

- Determine the escape rate via Jeans escape.
- Determine the escape rate via photochemical loss.
- Determine the escape rate of pick-up ions.
- Determine the escape rate via pick-up-ion sputtering.
- Determine the escape rate via ion outflow
- Determine the escape rate via charge-escape loss
- Determine the escape rate via bulk plasma momentum transfer

MAVEN Science and Measurement Objectives (3 of 3)

Science Objective	MAVEN Science Obj.	MAVEN Measurement Obj.
What has been the total loss to space through time?	Determine the relative escape rates of the stable isotopes and the resulting isotopic fractionation	Measure the ratios of stable isotopes (C, O, N, Ne, ^{40}Ar) between the homopause and the exobase
		Measure the ratios of stable isotopes (D/H, ^{38}Ar) in the vicinity of the homopause

Solar Wind Electron Analyzer (SWEA)

Instrument Accommodation	
• Large field of view with minimal obstructions • Conducting, grounded surfaces in the field of view • Sensor head in shadow (electronics box sunlit) • Simultaneous magnetic field measurements	

SWEA

Hemispherical top-hat electrostatic analyzer with deflection system

Mass	1.4 kg
Power	1 Watt
Energy range	5 eV - 6 keV
Energy res.	11% ($\Delta E/E$)
Field of view	$360° \times 130°$
Angular res.	$22.5° \times 7°$
Geom. factor	0.01 cm^2 ster

Measurements

• Energy and angular distributions of solar wind and magnetosheath electrons and ionospheric photoelectrons:

0 – 3 keV (full angle range)

3 – 6 keV (limited angle range)

• Continuous measurements throughout the orbit with 10-sec (20-40 km) resolution to resolve magnetic cusps and bow shock

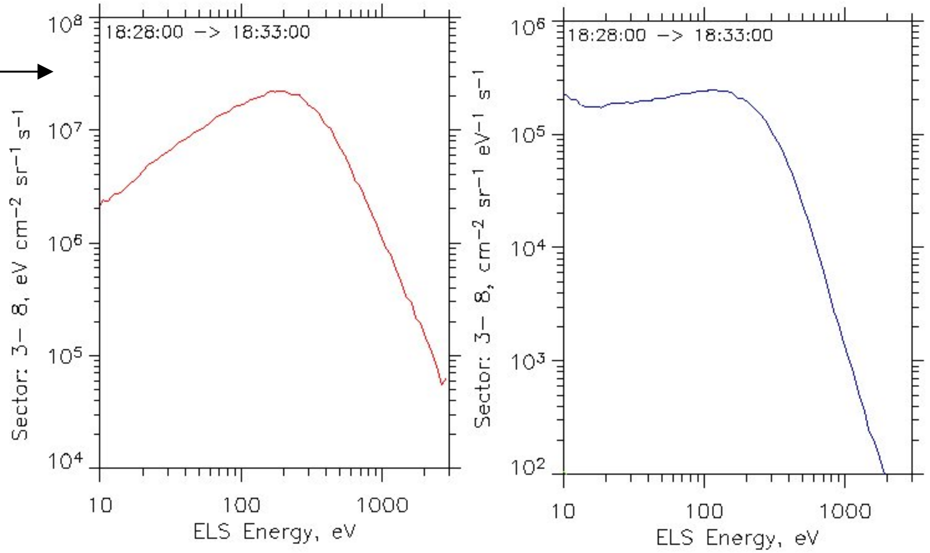
Science Objectives

• Electron impact ionization rate
• Magnetic field topology (with MAG)
• Plasma regime
• Photoelectron energy spectra
• Auroral electron features
• Solar wind interaction with Mars (with SWIA, STATIC, MAG, LPW)

Launch: end of 2013

Electron differential flux in the different regions of the Martian environment (MEx)

Dayside magnetosheath and Plasmasheet →



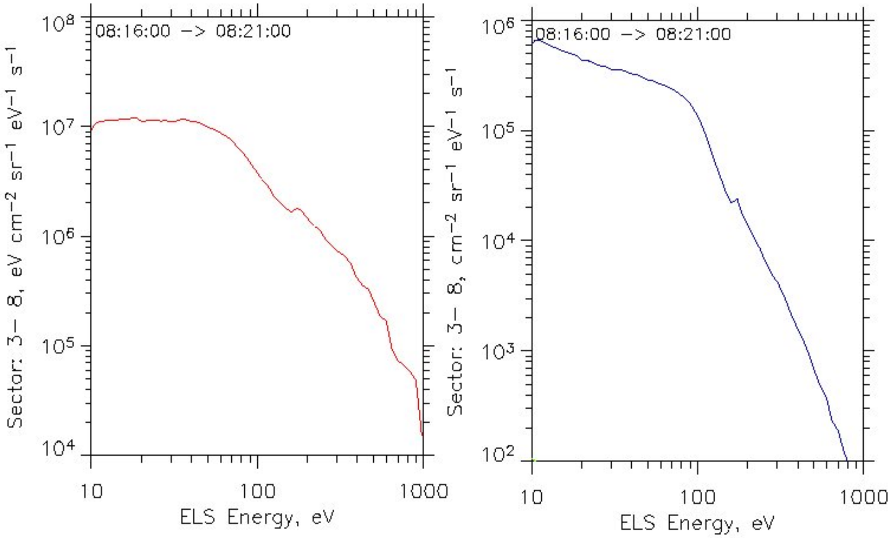
Maximum energy flux estimate

1.10^{8} eV cm^{-2} sr^{-1} eV^{-1}

For 16 azimuthal sectors and
Maximum count rate of 10^{5} s^{-1}
gives a geometrical factor of one sector

$GF_{16}=1.10^{-3}$ cm^{2} sr eV/eV

Plasmasheet



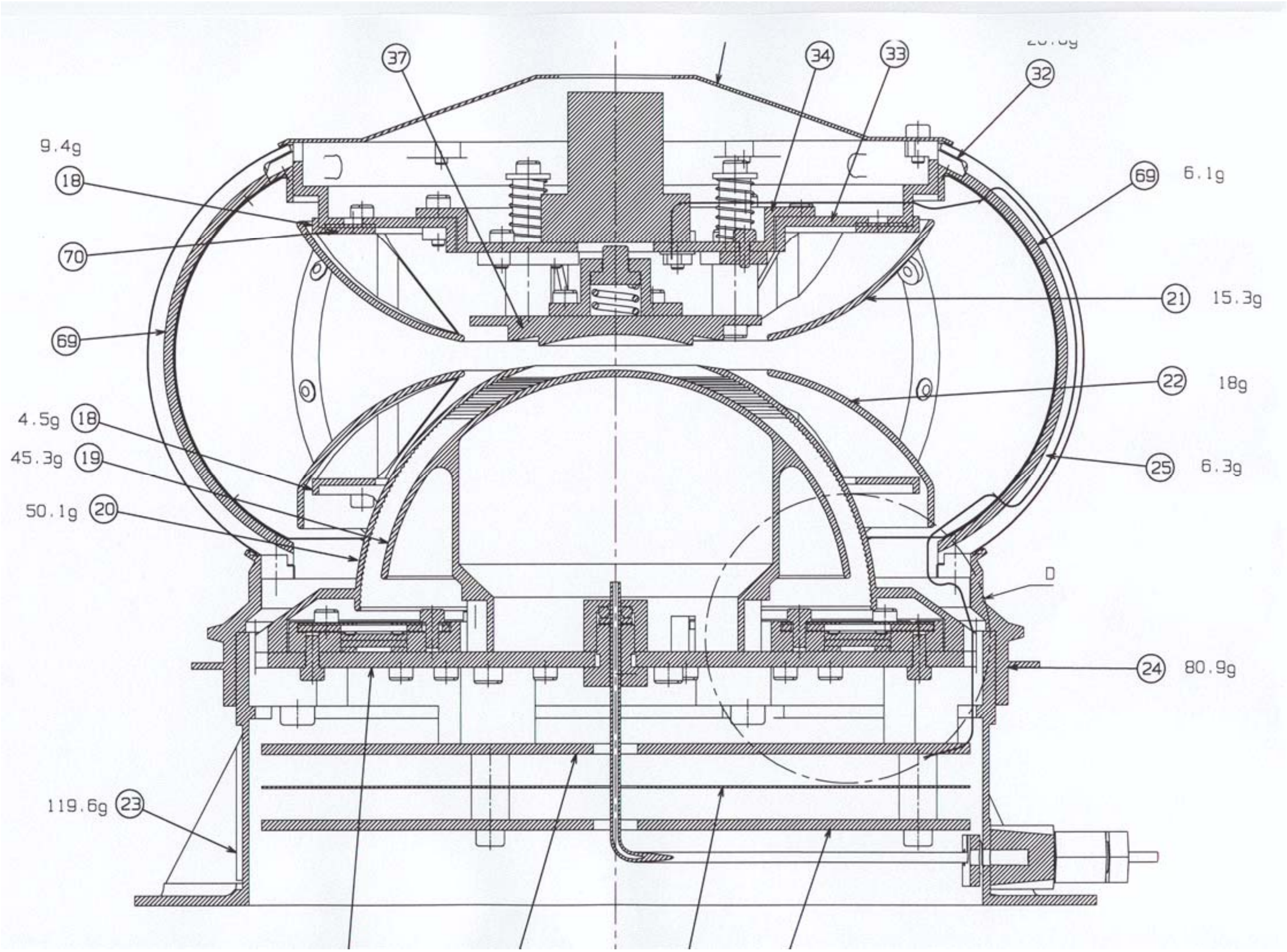
Stereo SWEA: $GF_{16}=2.10^{-3}$ (ideal)
$= 5.10^{-4}$ (real)

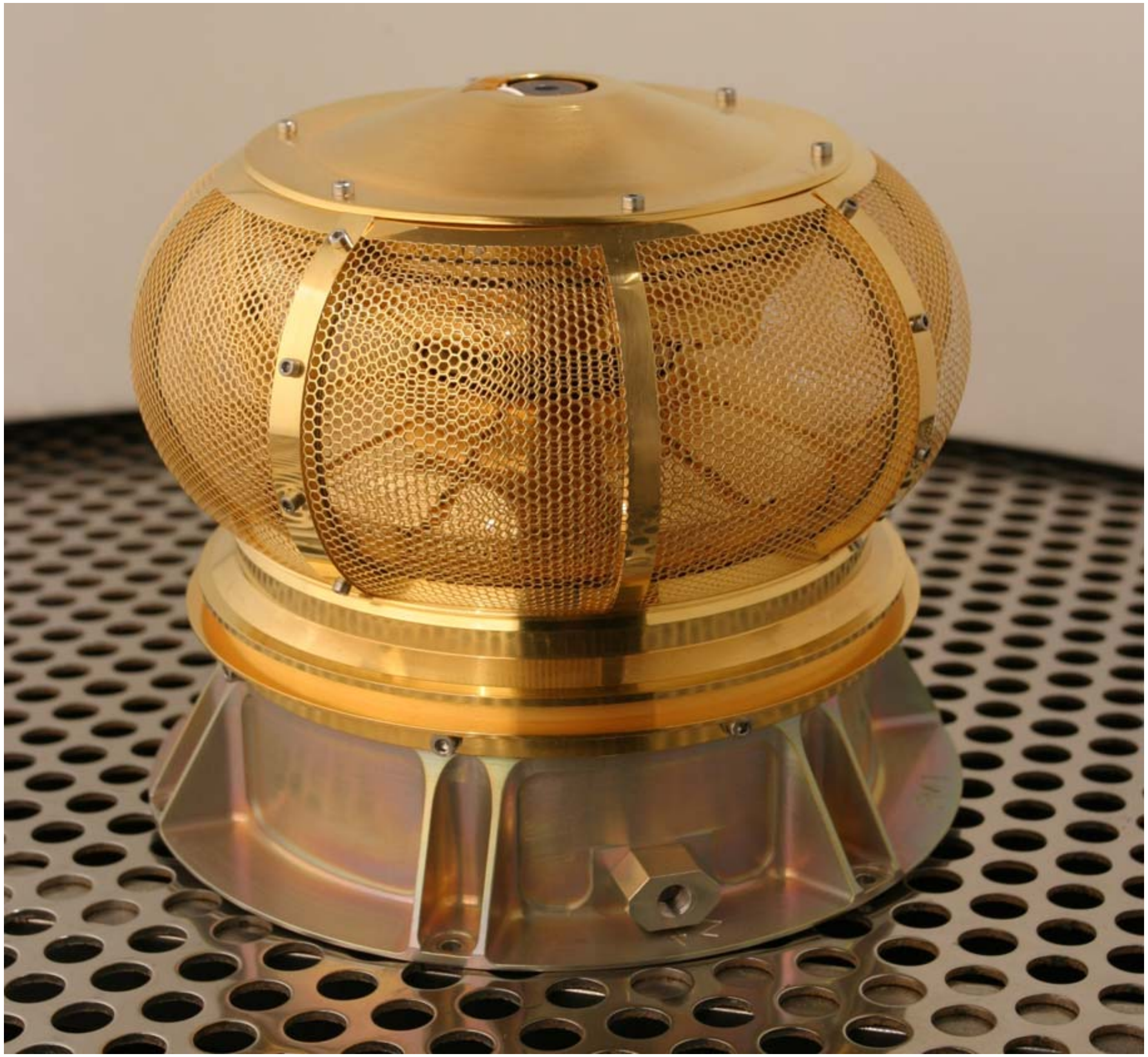
MGS ER: $GF_{16}=4.10^{-5}$

MEx ELS: $GF_{16}=4.7\ 10^{-5}$

Both far from saturation

Hardware Implementation: Baseline STEREO SWEA Design



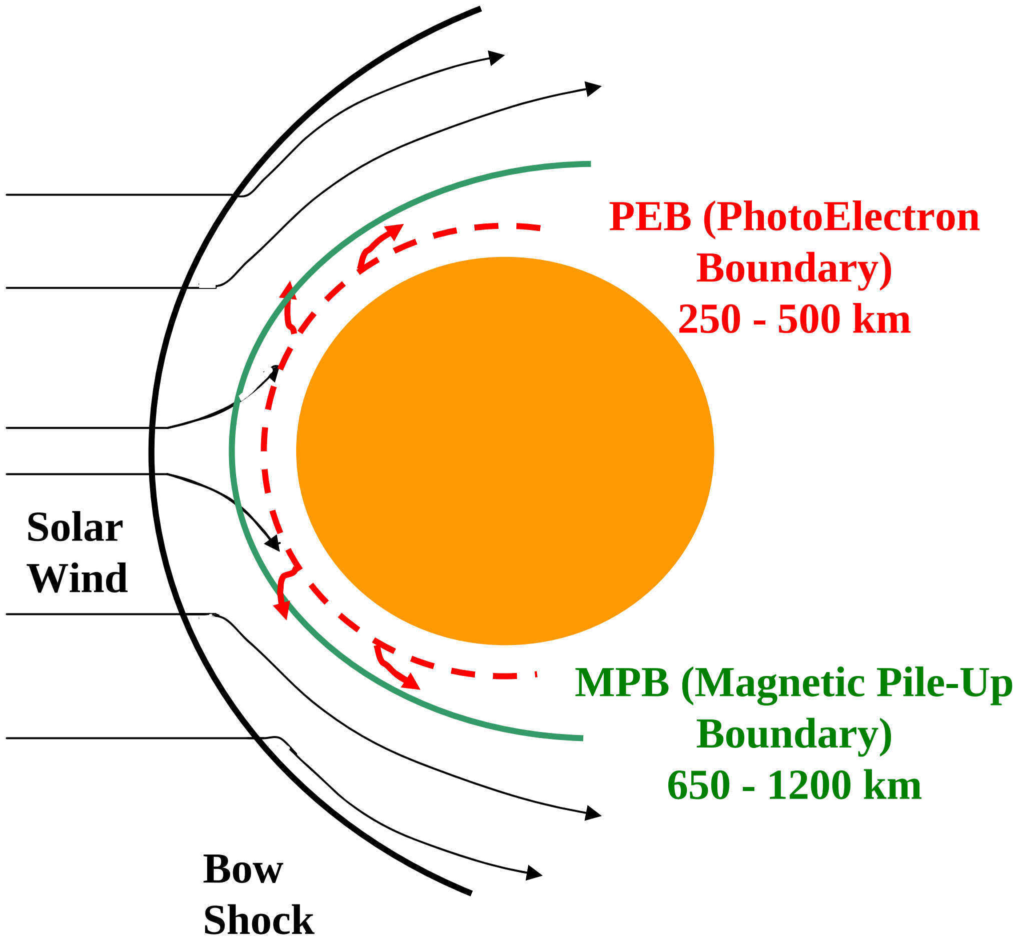


Science Topics

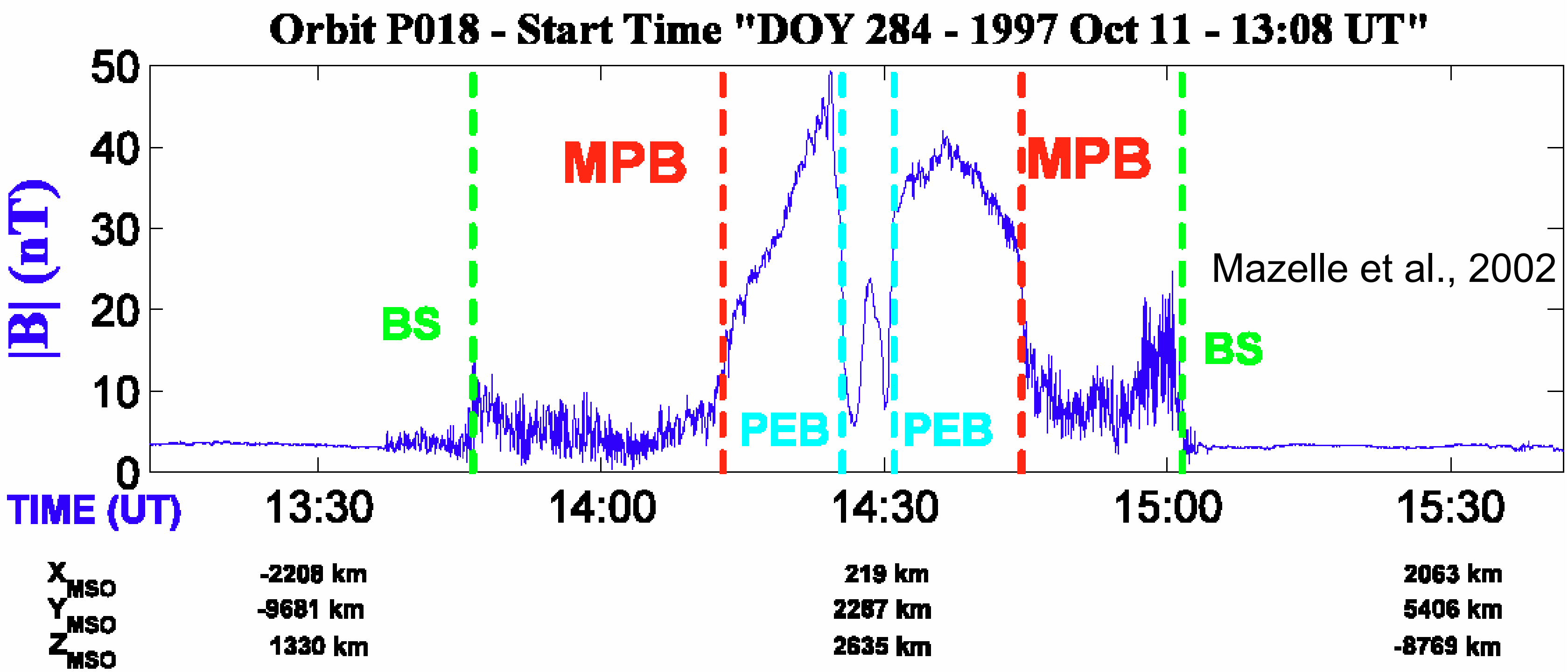
- Plasma boundaries: nature and role. Relation with the atmospheric escape.
- Upstream atmospheric escape.
- Ionospheric photo-electrons.

The three main martian plasma boundaries

- Bow shock
- Magnetic Pile-Up Boundary (MPB)
- Photoelectron Boundary (PEB) or ionopause



The Martian Magnetic Pileup Boundary (MPB)

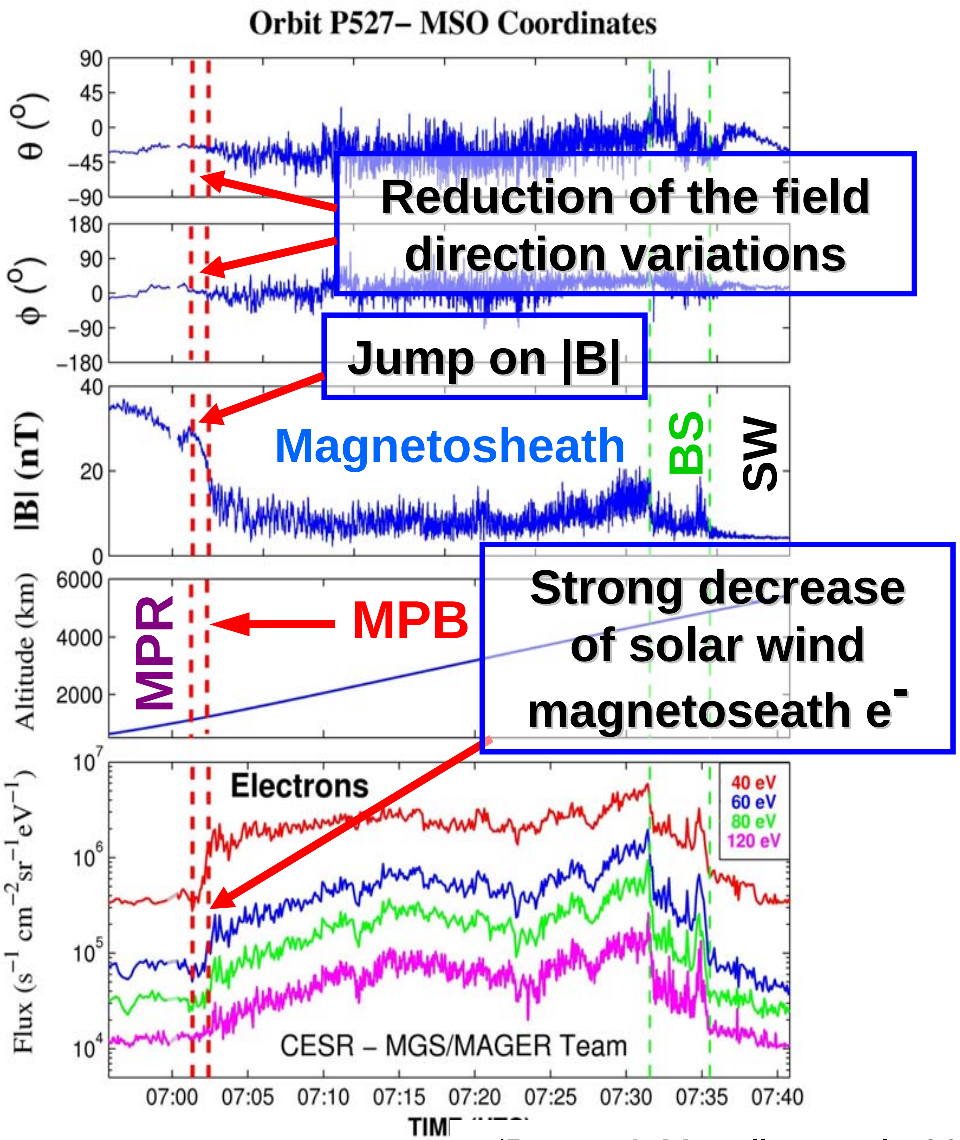


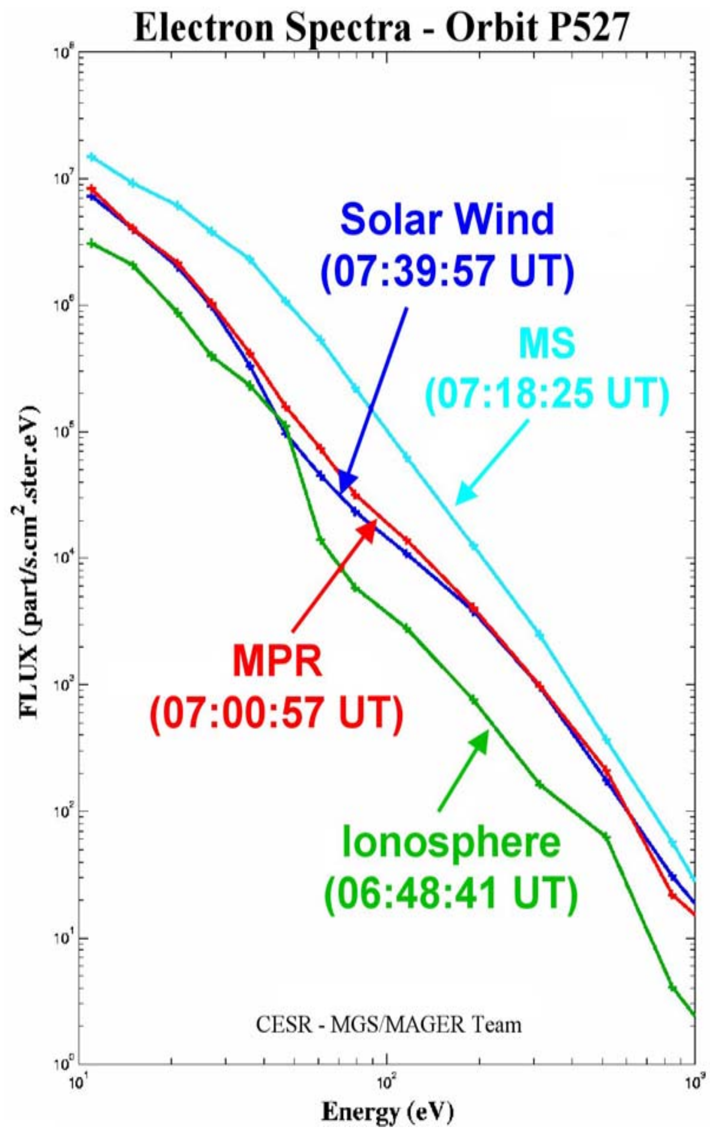
- Sudden increase in the magnetic field pileup
- Increase of draping
- Cooling of electron distribution

PEB: "Photo-electron boundary" [Mitchell et al., 2001] (MGS)

PVO name: ionopause at Venus (pressure balance boundary for solar max conditions)

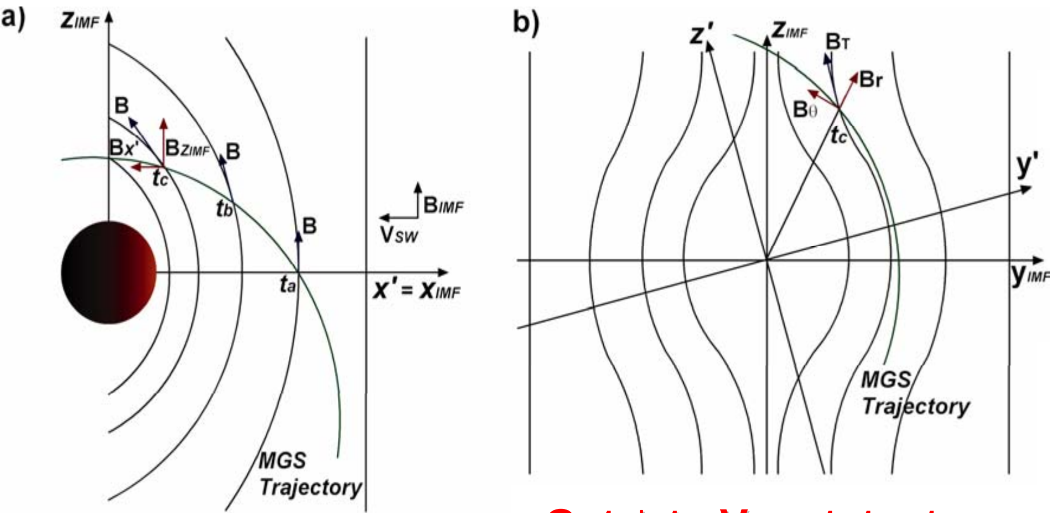
The Martian MPB according to MGS





(Bertucci, Mazelle, et al., 2003)

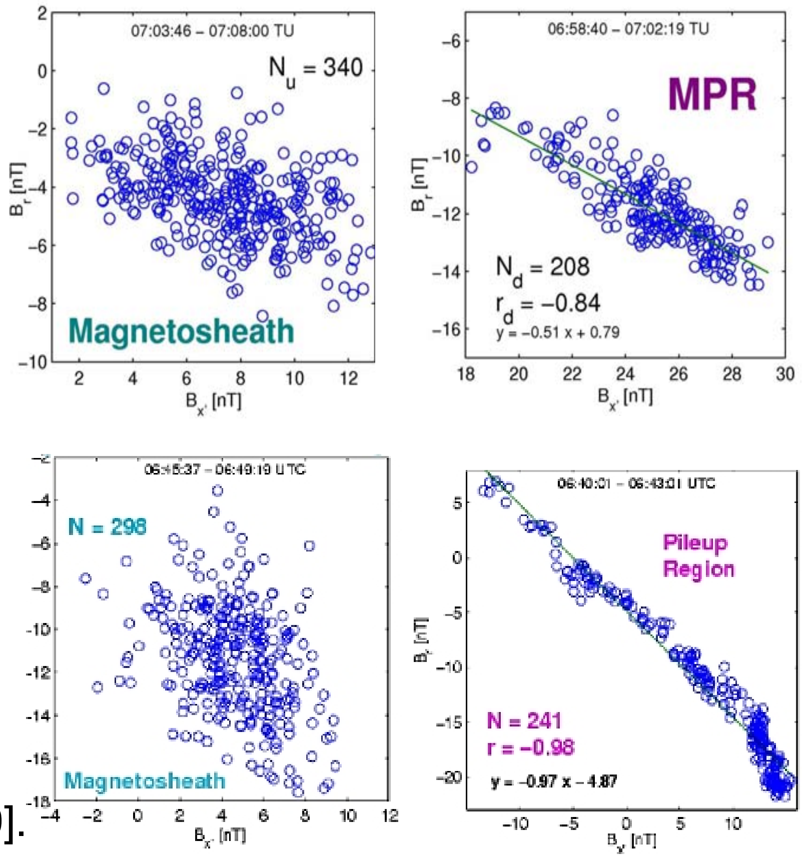
Martian MPB: Draping Enhancement



Cut ⊥ to V_{sw} at $t = t_c$

Correlation between $B_{x'}$ and B_r

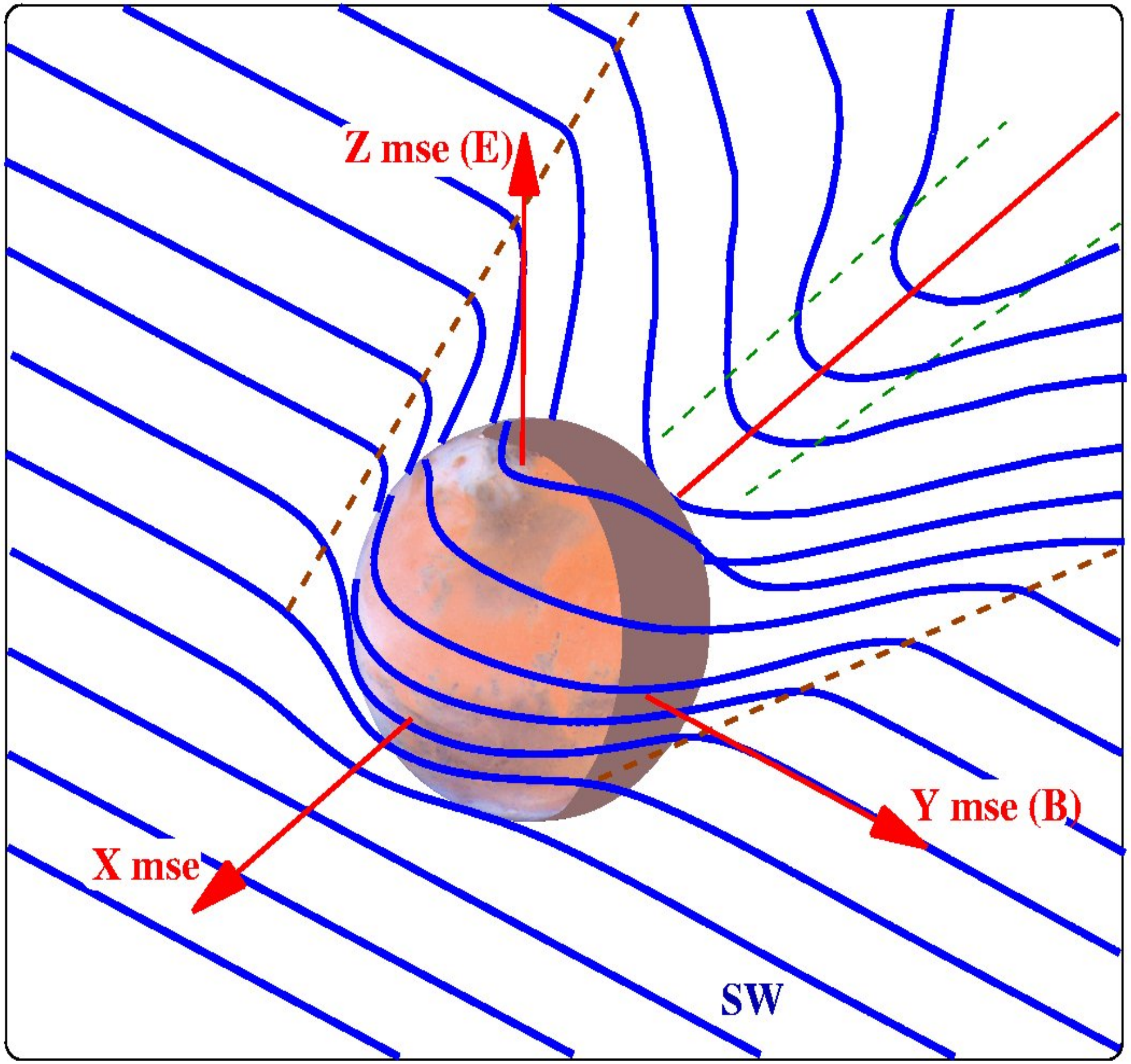
2 examples comparing upstream and downstream from the MPB:



IMF draping is revealed from the correlation between axial component ($B_{x'}$) and transverse *e.g.*, radial (B_r)

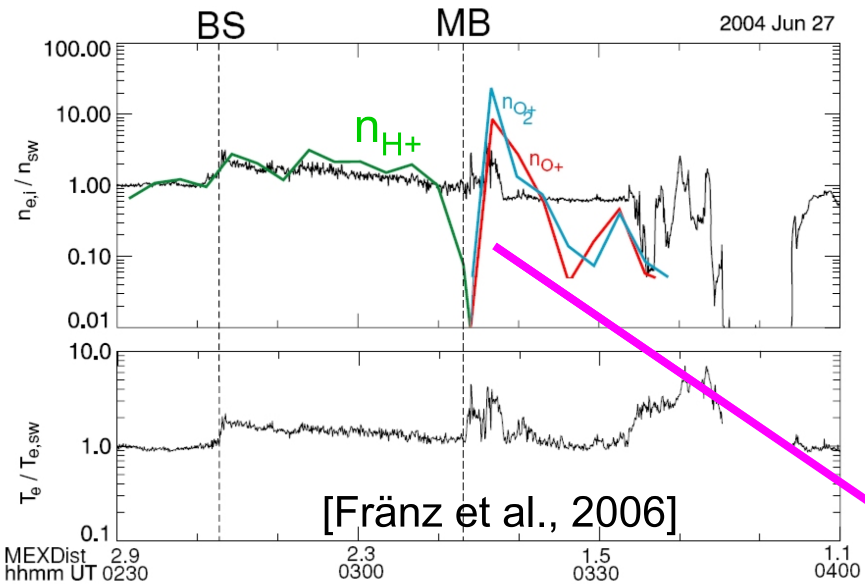
Draping on the dayside is significant only downstream from the MPB whatever the |B|-gradient
[*Bertucci, Mazelle, et al.*, 2003a]

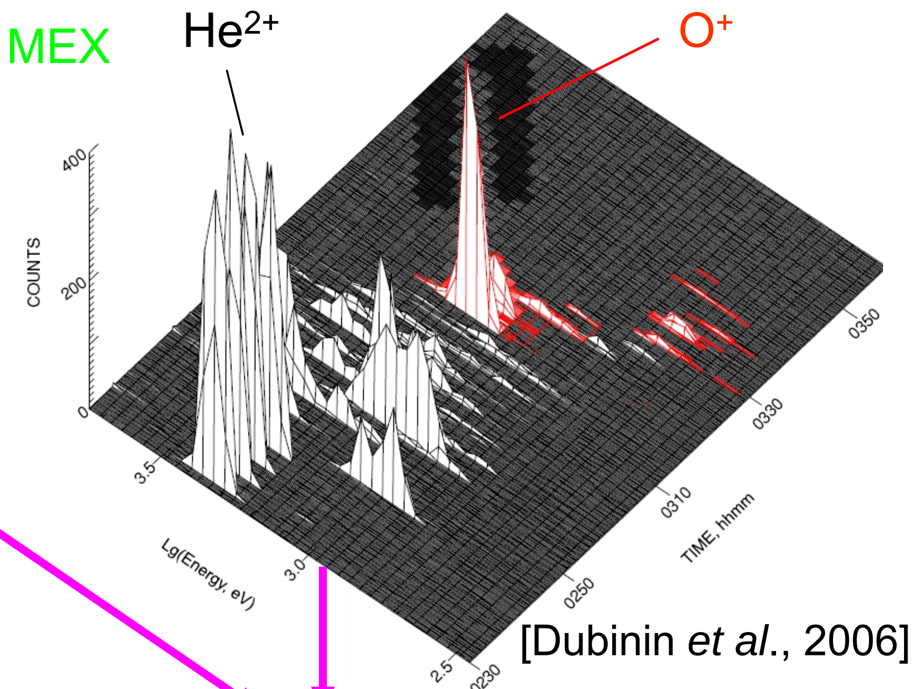
Similar properties reported across the magnetic tail boundary [Yeroshenko et al., 1990].



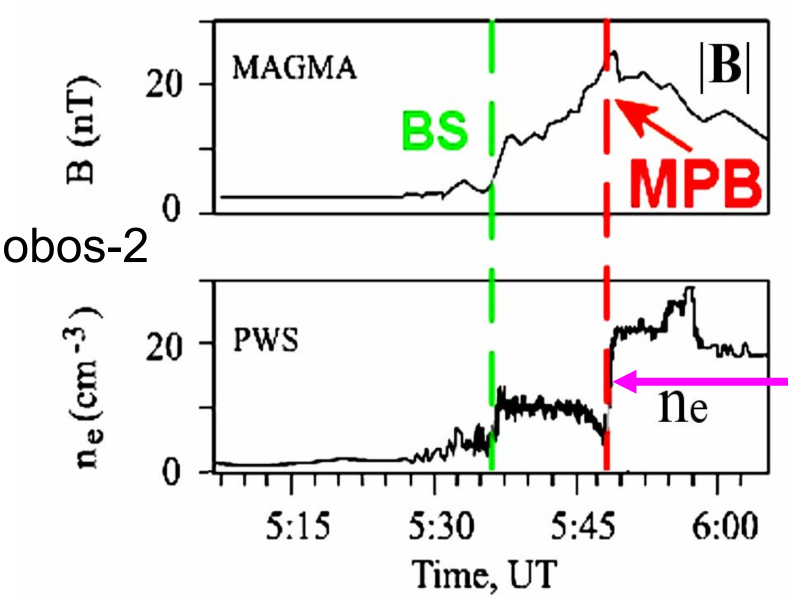
Z mse (E)
Y mse (B)
X mse
SW

Particle density variations





Solar wind ions are replaced by planetary ions.



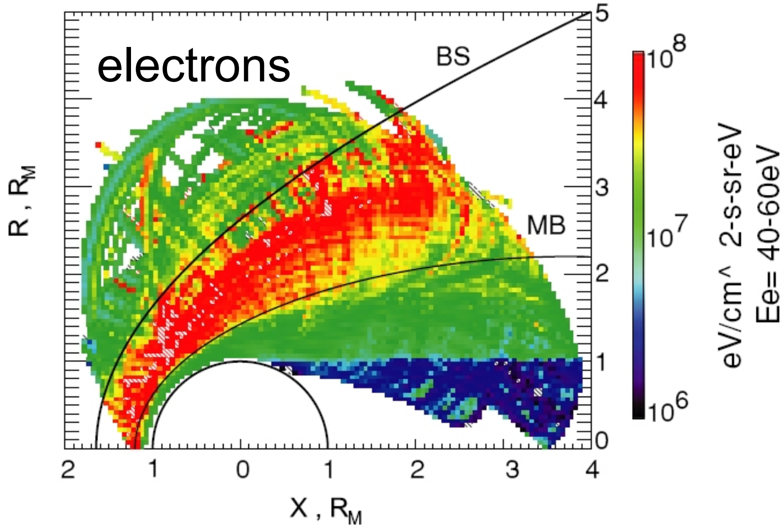
Phobos-2

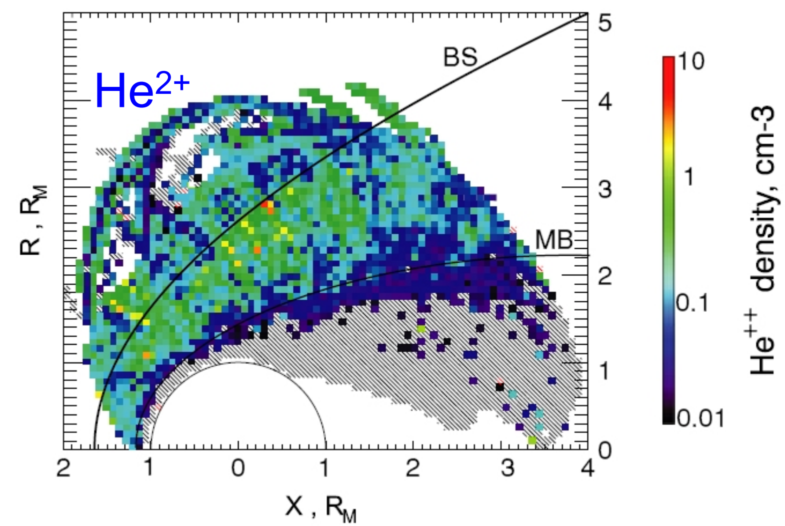
Total e^- density increases (mainly cold electrons). Cooling of the e^- distribution.

Confirmed by recent MARSIS results

Plasma populations: statistical studies

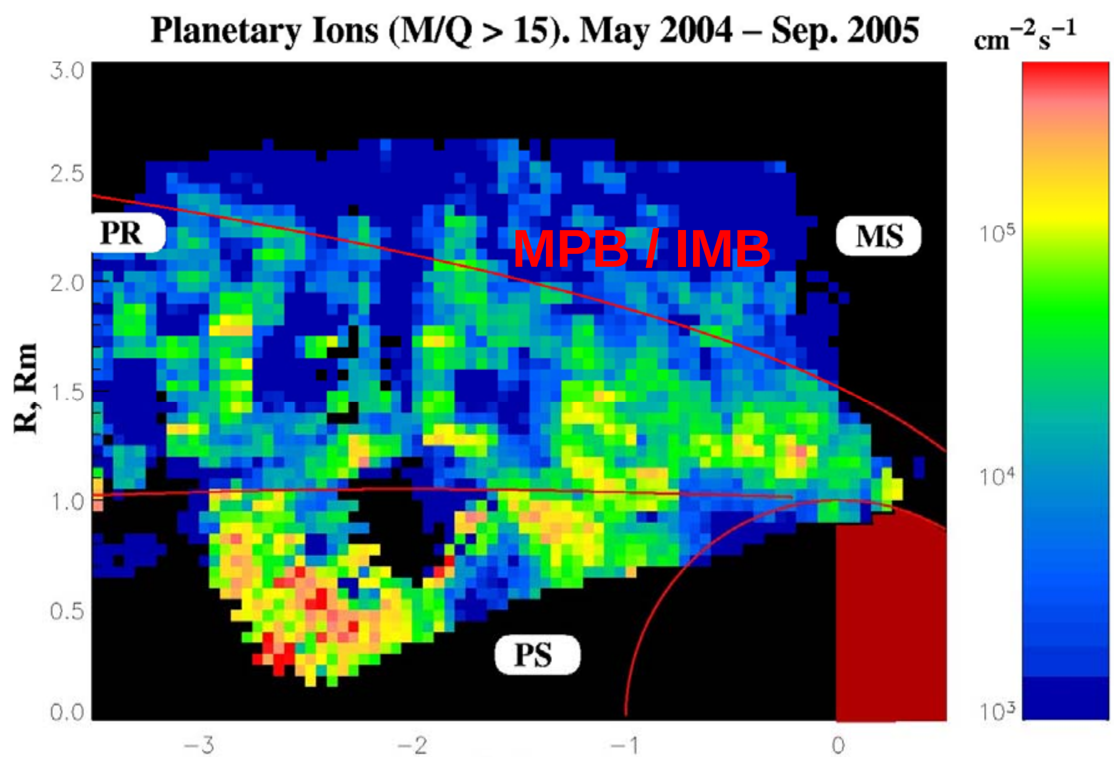
Solar wind populations





[Fränz et al., 2006]

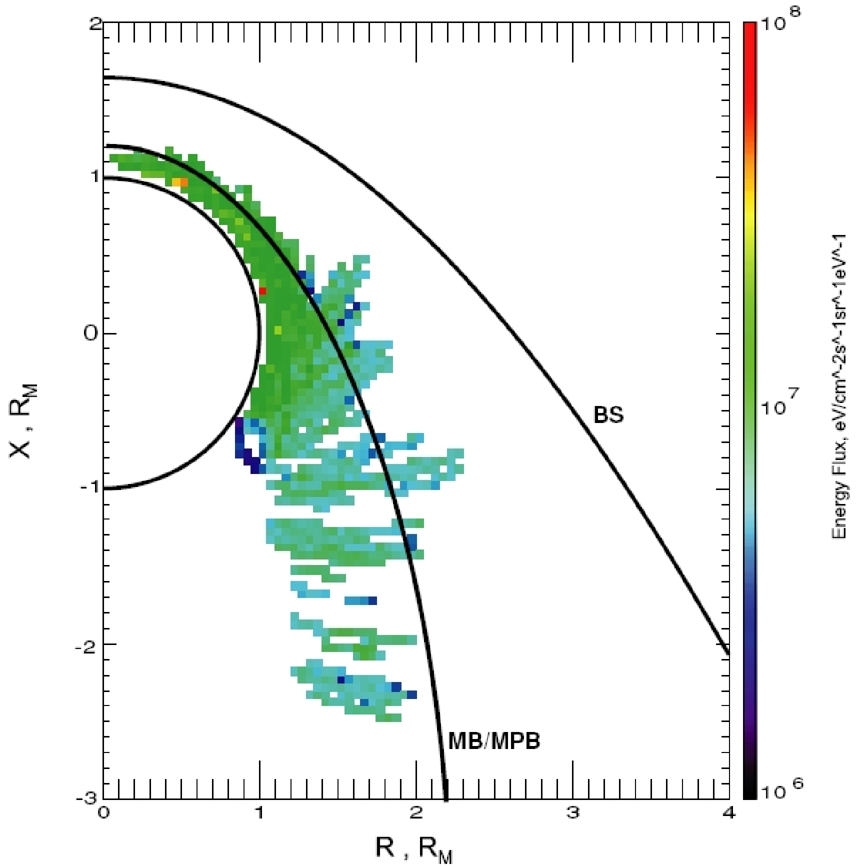
A stoppage of the solar wind occurs at the MPB which acts as an effective obstacle for the magnetosheath (solar wind) plasma



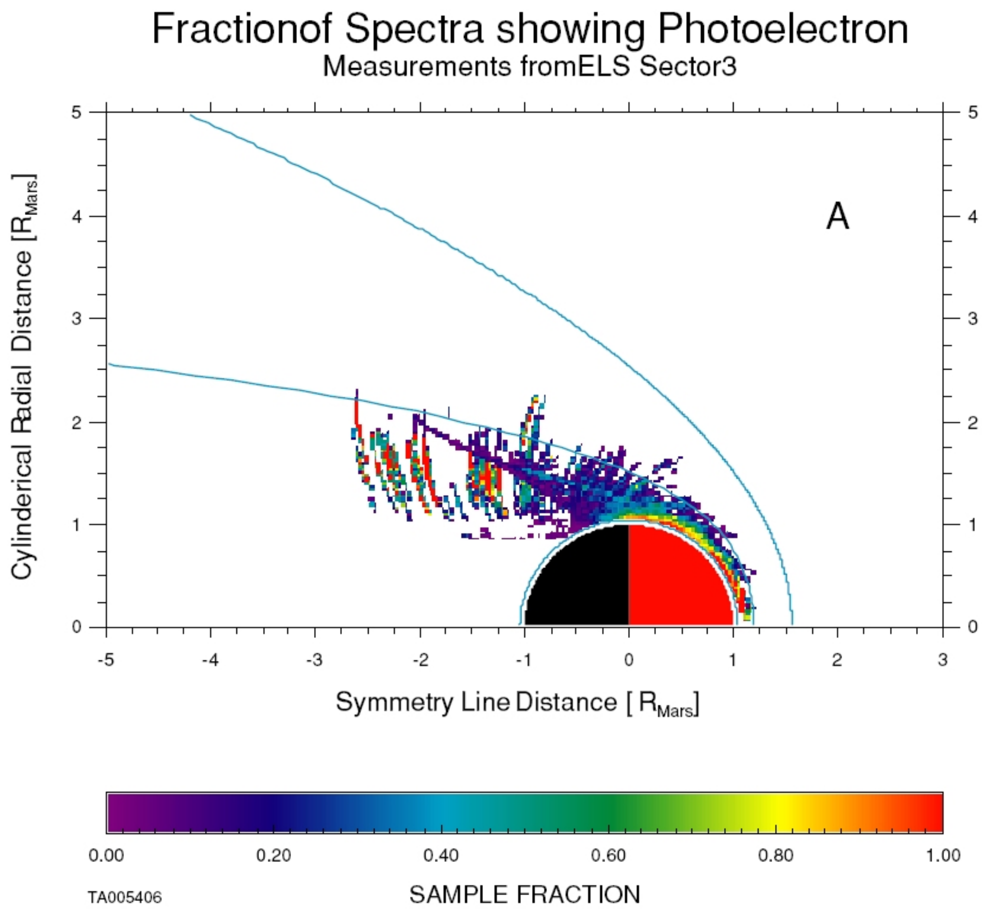
[Fedorov *et al.*, 2006]

Strong confinement by the MPB of the nightside planetary escape

Statistics of the observations of photoelectrons



[Dubinin et al., 2006]

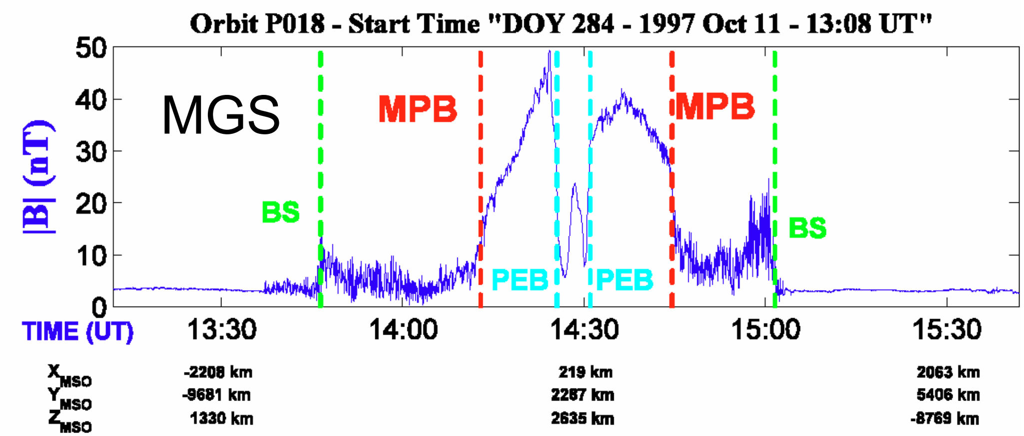


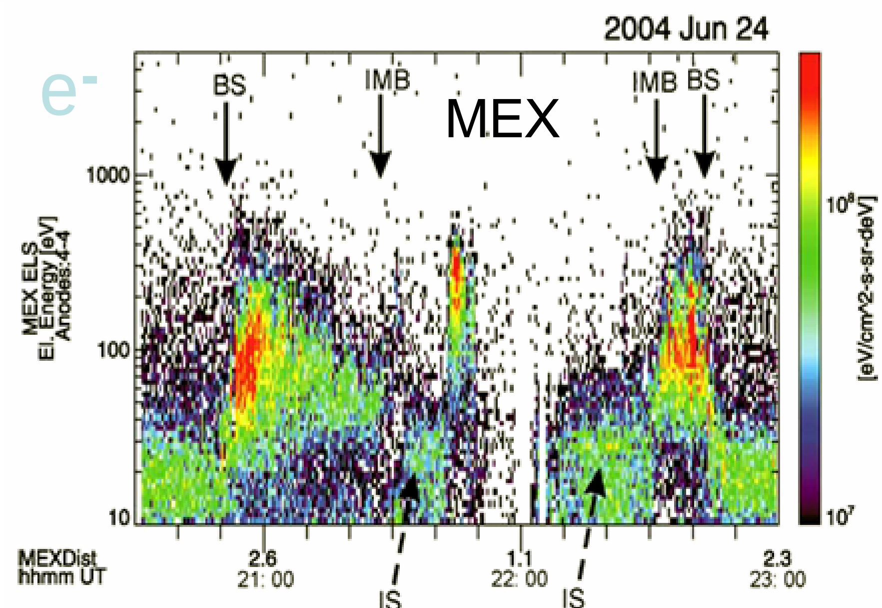
[Frahm et al., 2006]

high-altitude photoelectrons are the result of direct magnetic connectivity to the dayside ionosphere inside the induced magnetosphere [Liemohn *et al*., 2006]

The Martian magnetic pileup boundary a.k.a. induced magnetosphere boundary

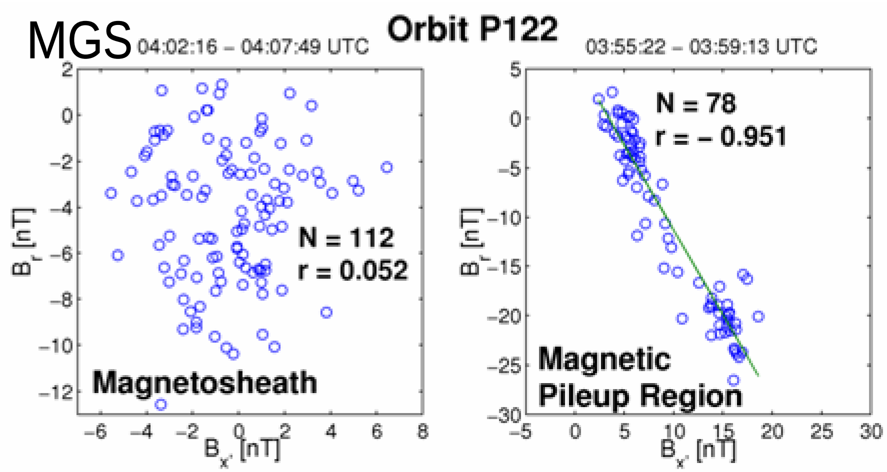
Mazelle et al., 2002





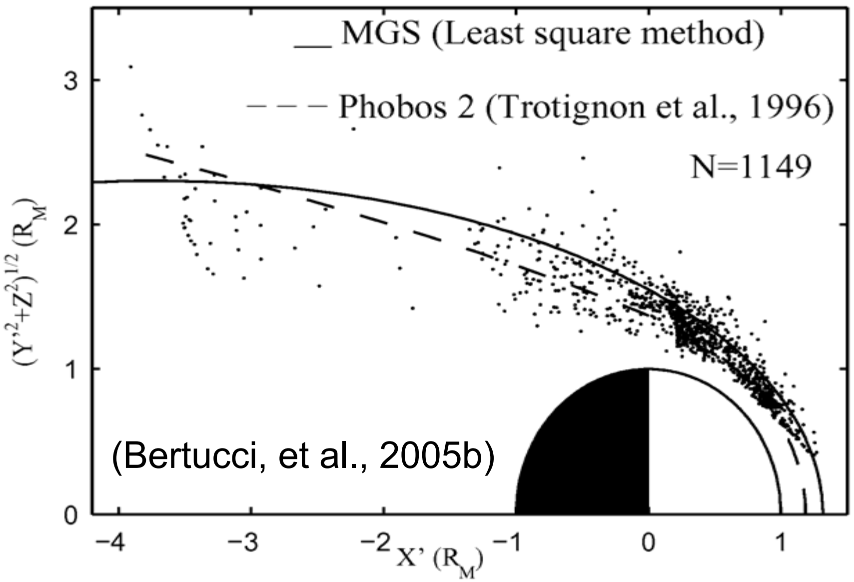
Dubinin, et al., 2006

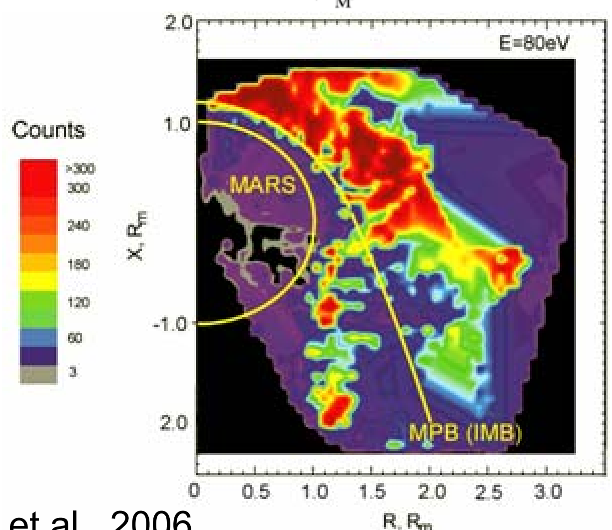
- Sudden increase in the magnetic field pileup on the dayside.
- Cooling of electron distribution.
- Decrease of SW ion density and velocity.
- Increase of the total plasma density.
- Increase of planetary ion density.
- Increase of draping.



Bertucci, Mazelle, et al., 2003

Martian MPB: macroscopic properties

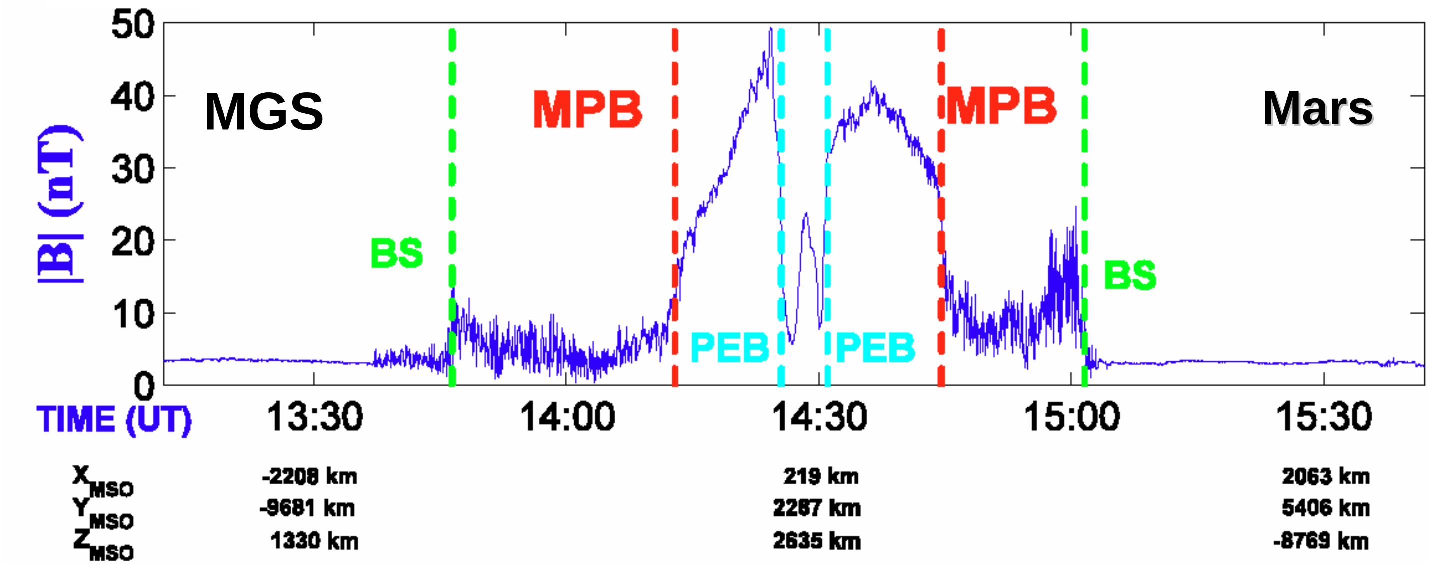


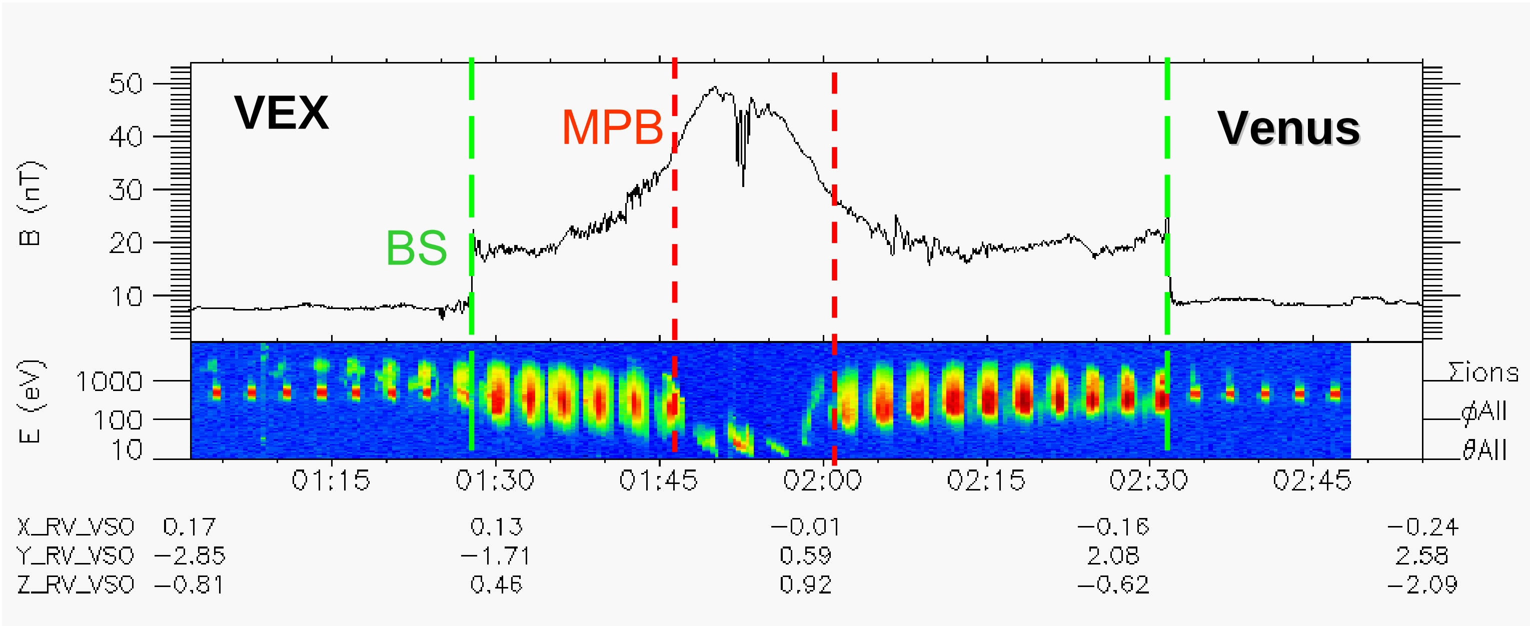


Dubinin, et al., 2006

- Position independent from solar cycle (Vignes et al., 2000).
- Correlation with BS position (Bertucci et al., 2005b).
- Influence from crustal fields (Crider et al., 2002).
- 80-eV electron fluxes clearly show the MPB separating the magnetosheath and barrier.
- Solar wind He++ and H+ show similar behavior.
- Accordingly, the planetary plasma receives the flux of momentum and escape (mainly O+) within the MPB (Dubinin et al., 2006).

Comparison Mars / Venus (1)



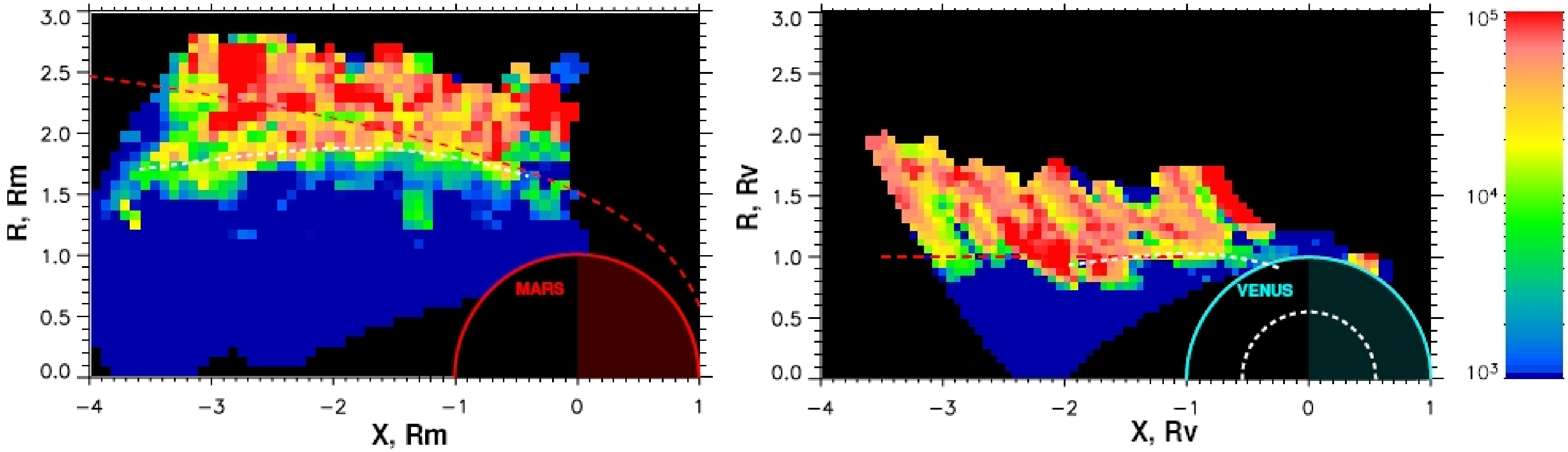


Comparisons Mars – Venus (2): Statistical Study

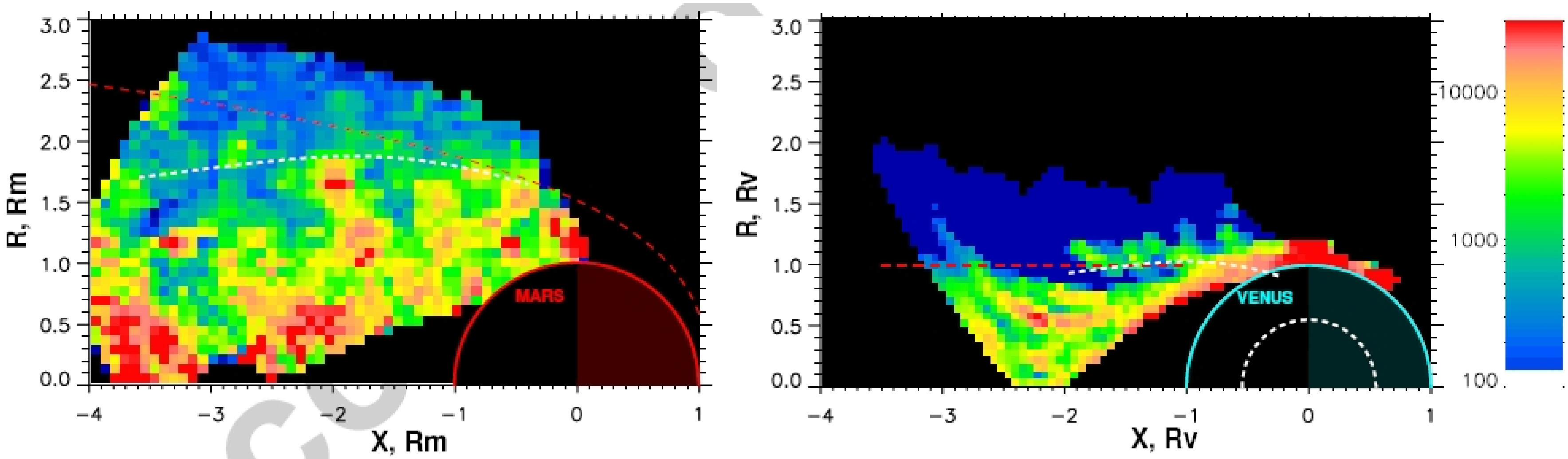
Mars

Solar wind ions:

Venus

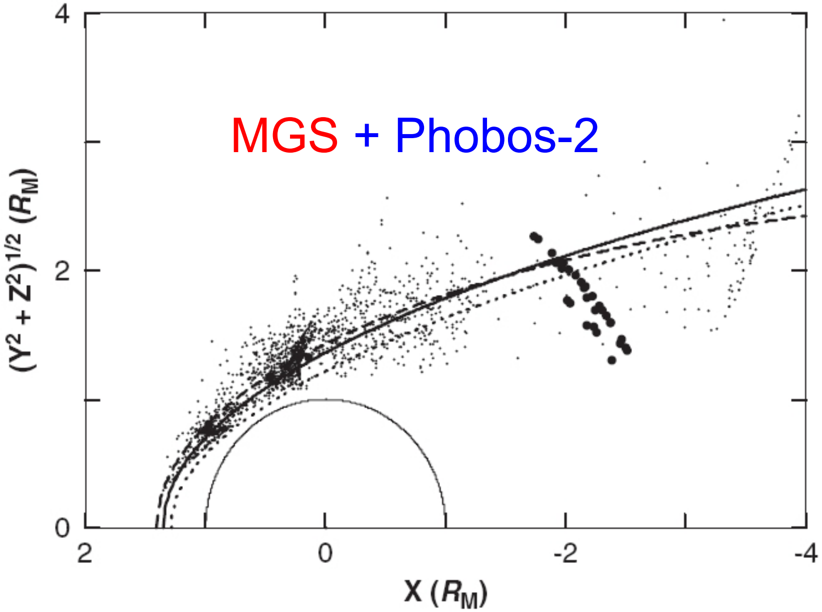


Planetary ions: O^+ and O^{2+}, any energy

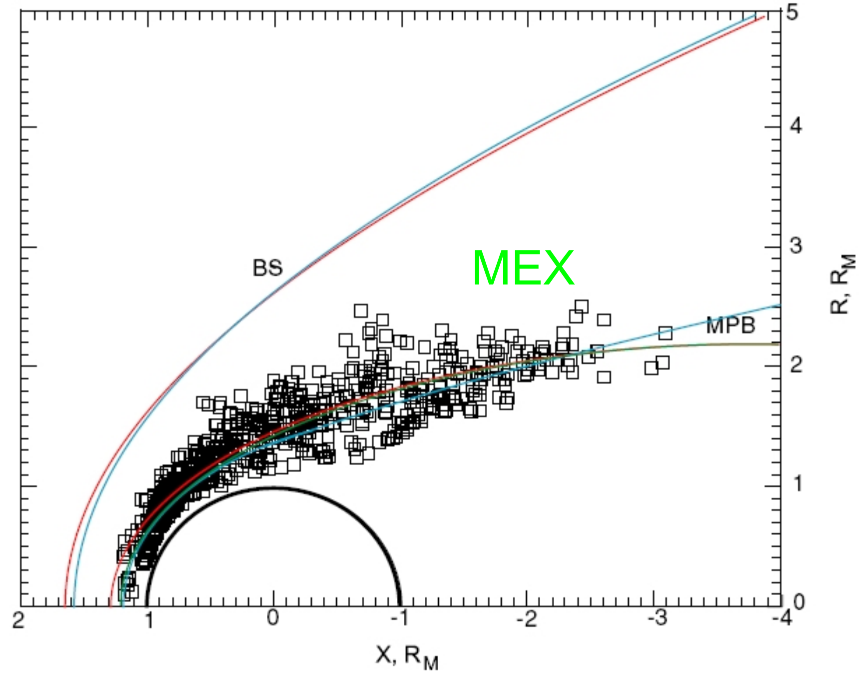


[Fedorov et al., 2007]

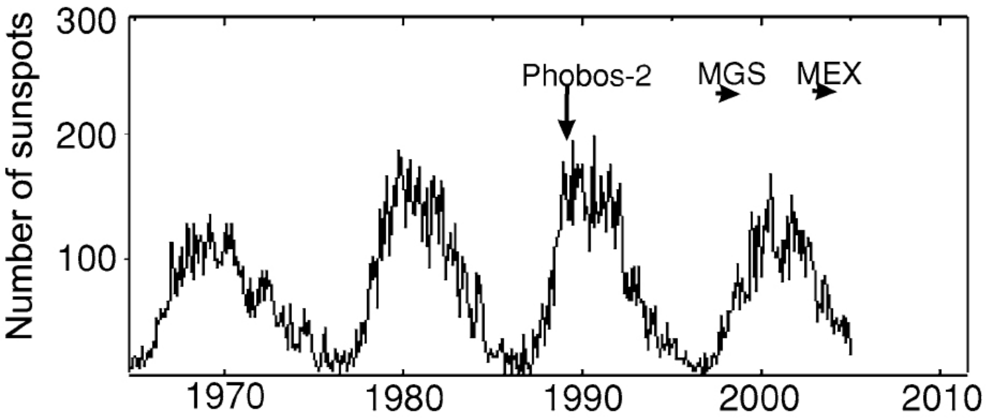
Statistics of the MPB positions at Mars



[Trotignon, Mazelle and Acuna, 2006]

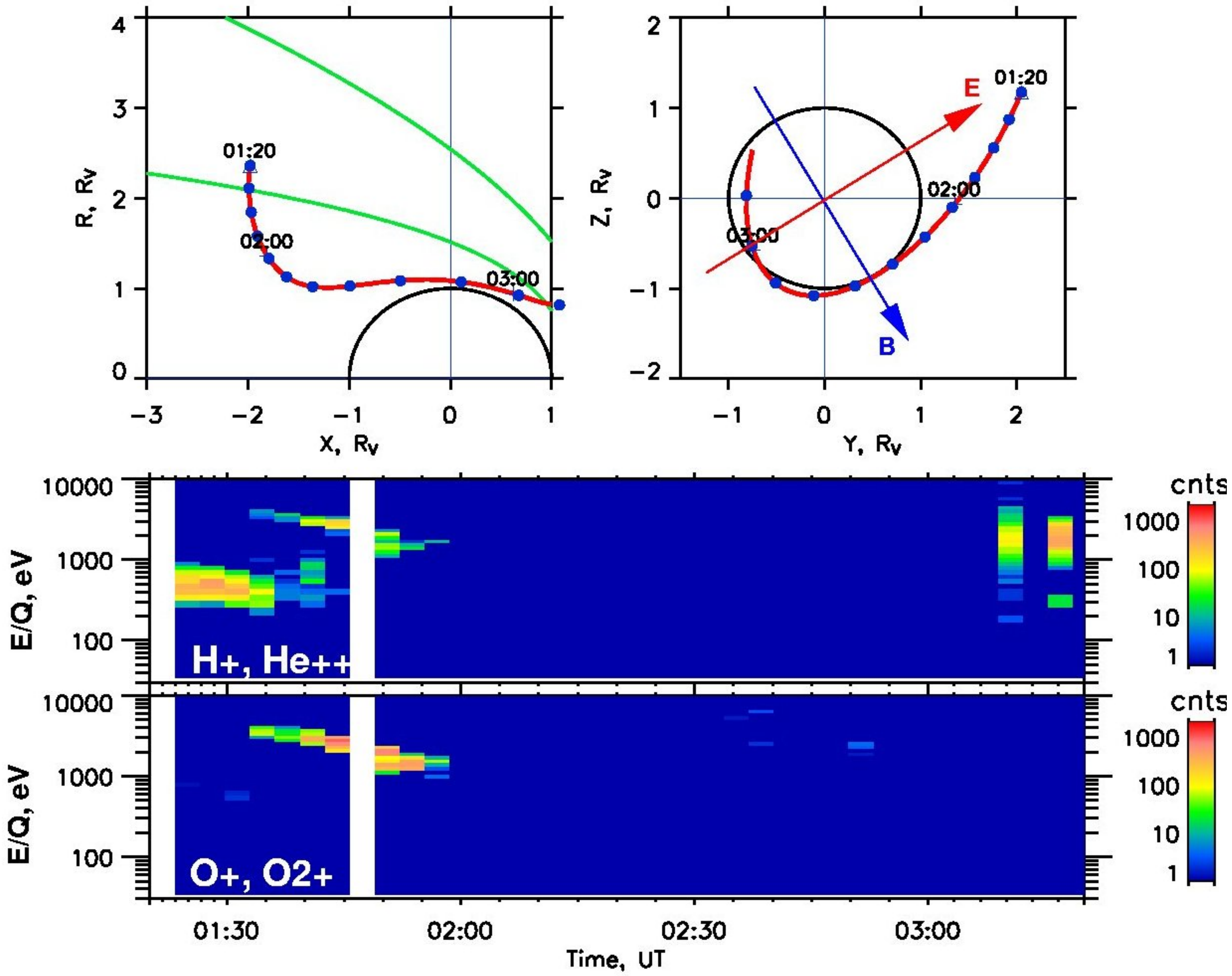


[Dubinin *et al*., 2006]



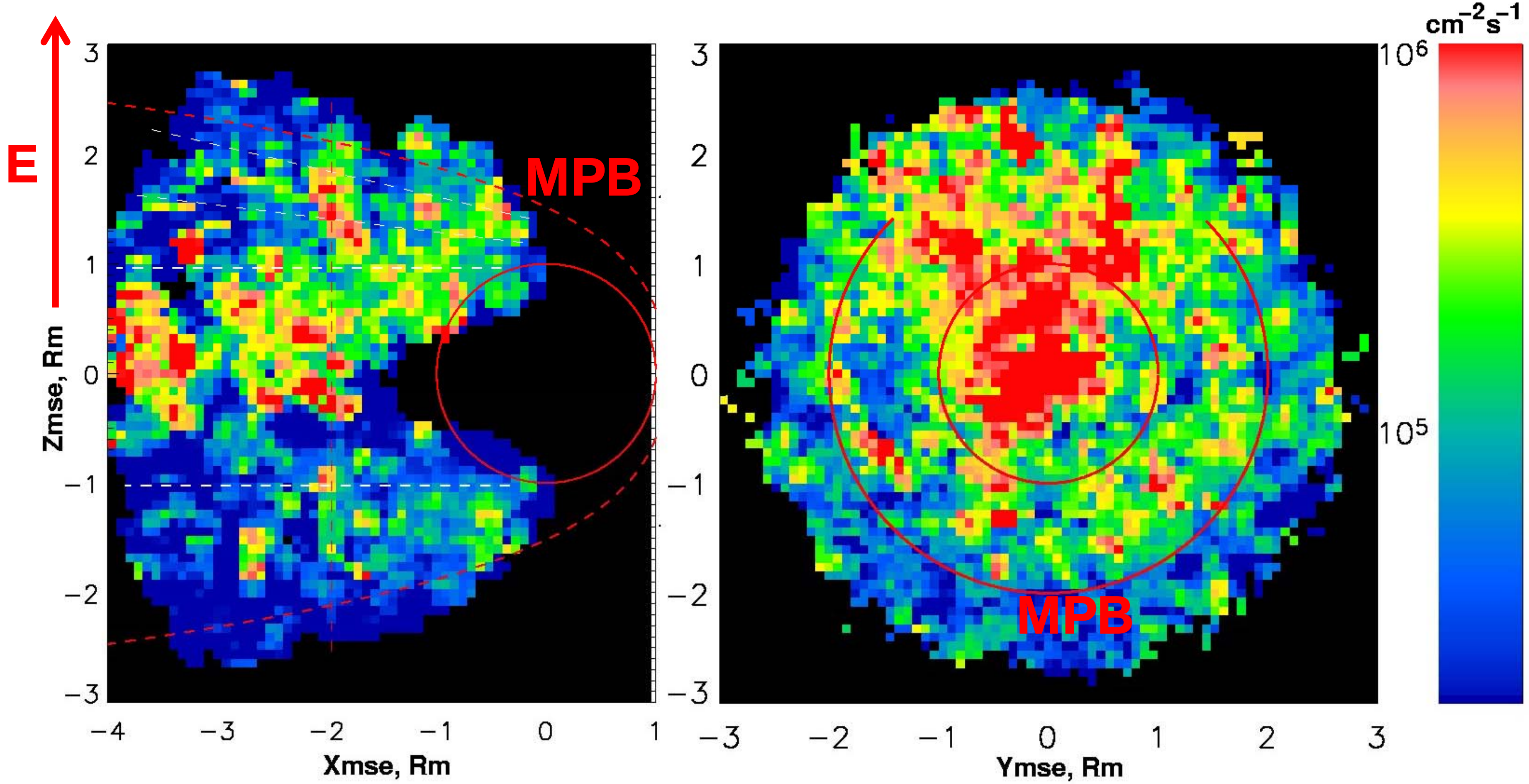
Mean location of the MPB nearly **insensitive to the solar cycle variations** as for the bow shock

MEX. An example of MPB crossing



Heavy planetary ions in the Martian tail

MEX IMA M/Q > 15 1 May 2004 - 30 May 2006



Total flux = 3.8 10^{23} s^{-1} [Barabash *et al.*, Science, 2007]

Heavy planetary ions in the Martian tail

MEX IMA M/Q > 15 1 May 2004 - 30 May 2006

at X_{MSO} = -2R_M

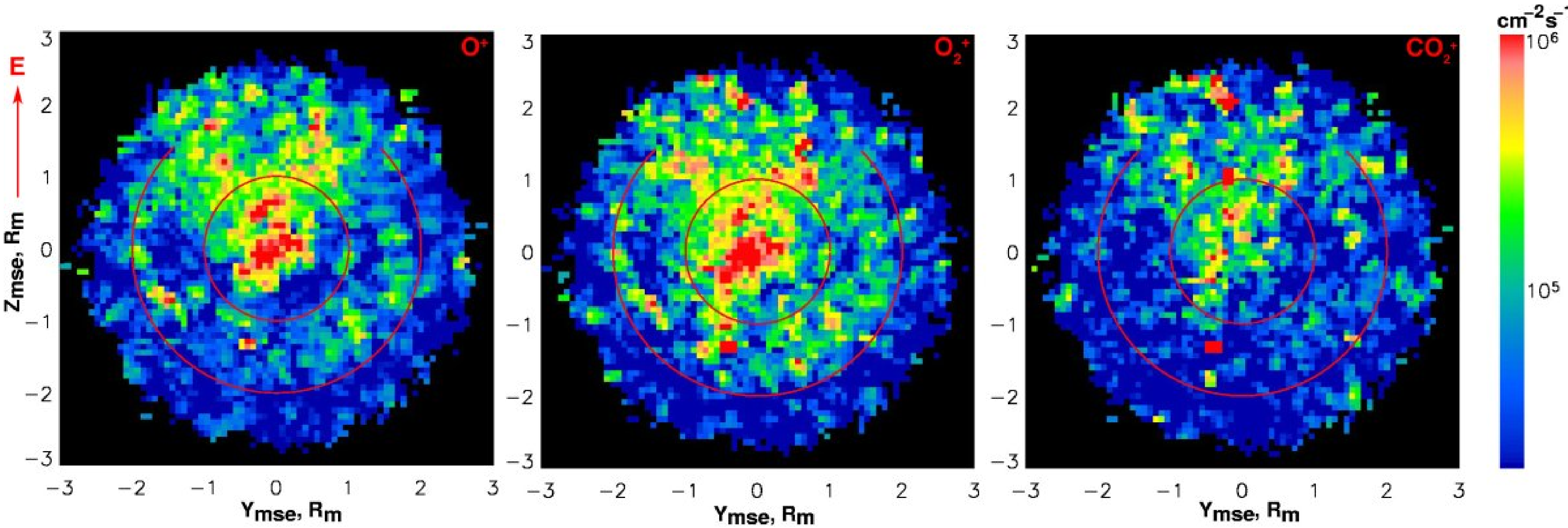
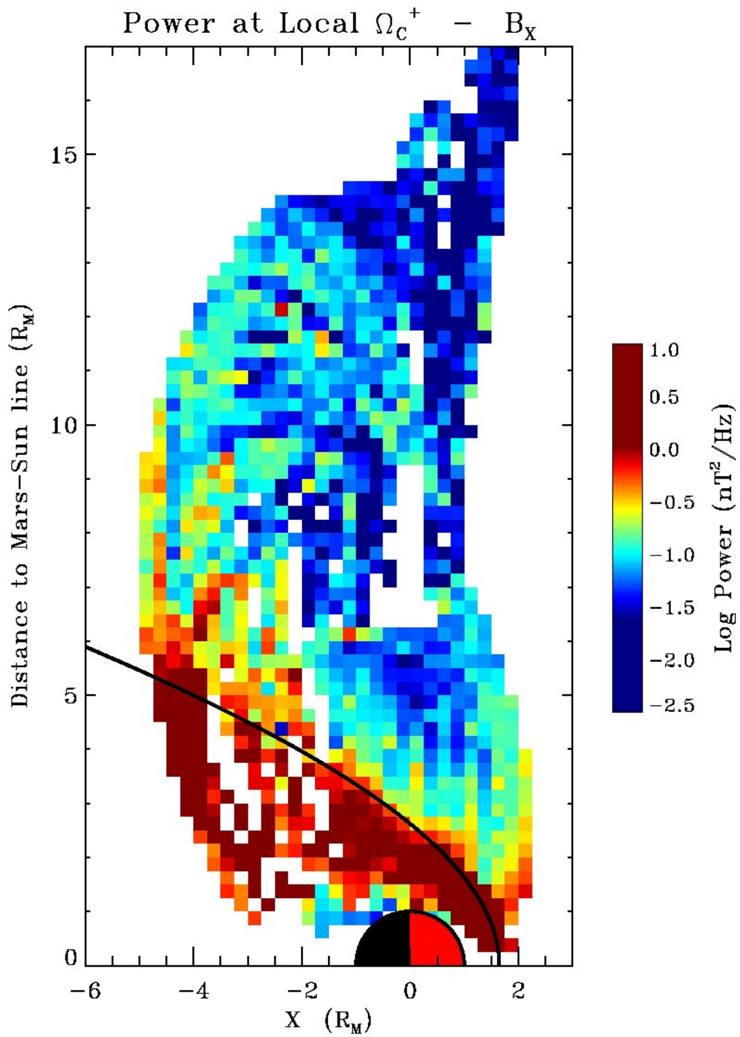


Fig. 2. *ZY* maps of the integral fluxes (cm^{-2} s^{-1}) of O^+ (**left**), O_2^+ (**middle**), and CO_2^+ (**right**). The fluxes are averaged over streamlines outside the eclipse and along the X_{MSE} direction inside the eclipse (Fig. 1). The average flux distribution is mapped onto the plane $X_{MSE} = -2R_M$ and collected in the $0.08R_M \times 0.08R_M$ pixel array. For the final distribution, only pixels that have been sampled at least five times were taken into account. All bins with fewer crossings were disregarded. For reference, we also show the Mars limb, the MPB cross section at the distance $x = -2R_M$. The direction of the interplanetary electric field is shown by the red vector.

[Barabash *et al.*, Science, 2007]

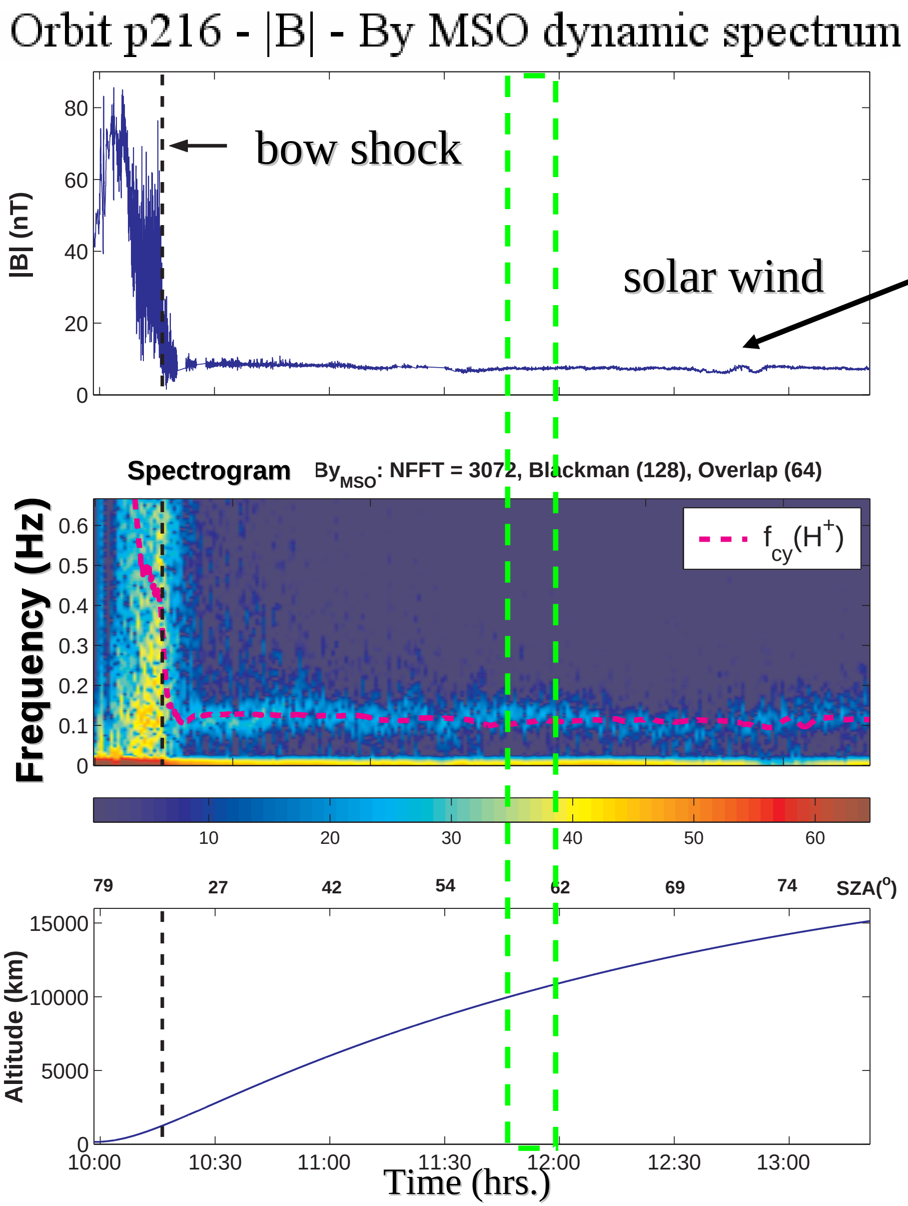
Low Frequency Upstream Waves at Mars: overview from MGS results



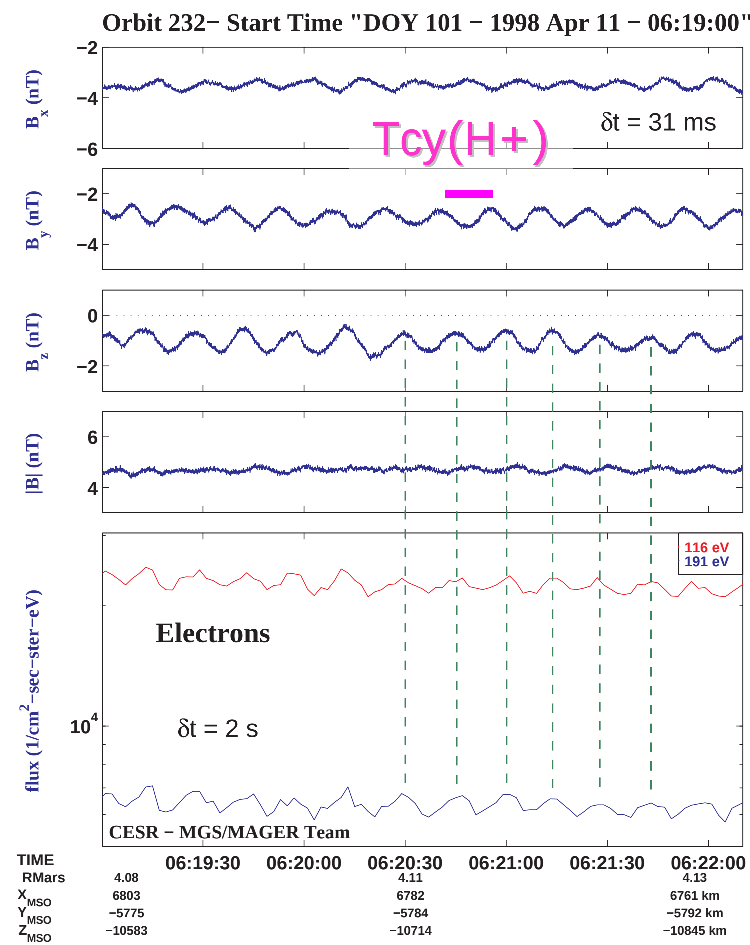
[Brain *et al*., *JGR*, 2002]

- Waves at the proton cyclotron frequency
- Evidence of the effect of the interaction with the exosphere (as for comets) outside the bow shock.
- link with the “erosion” of the planetary atmosphere (non thermal escape)

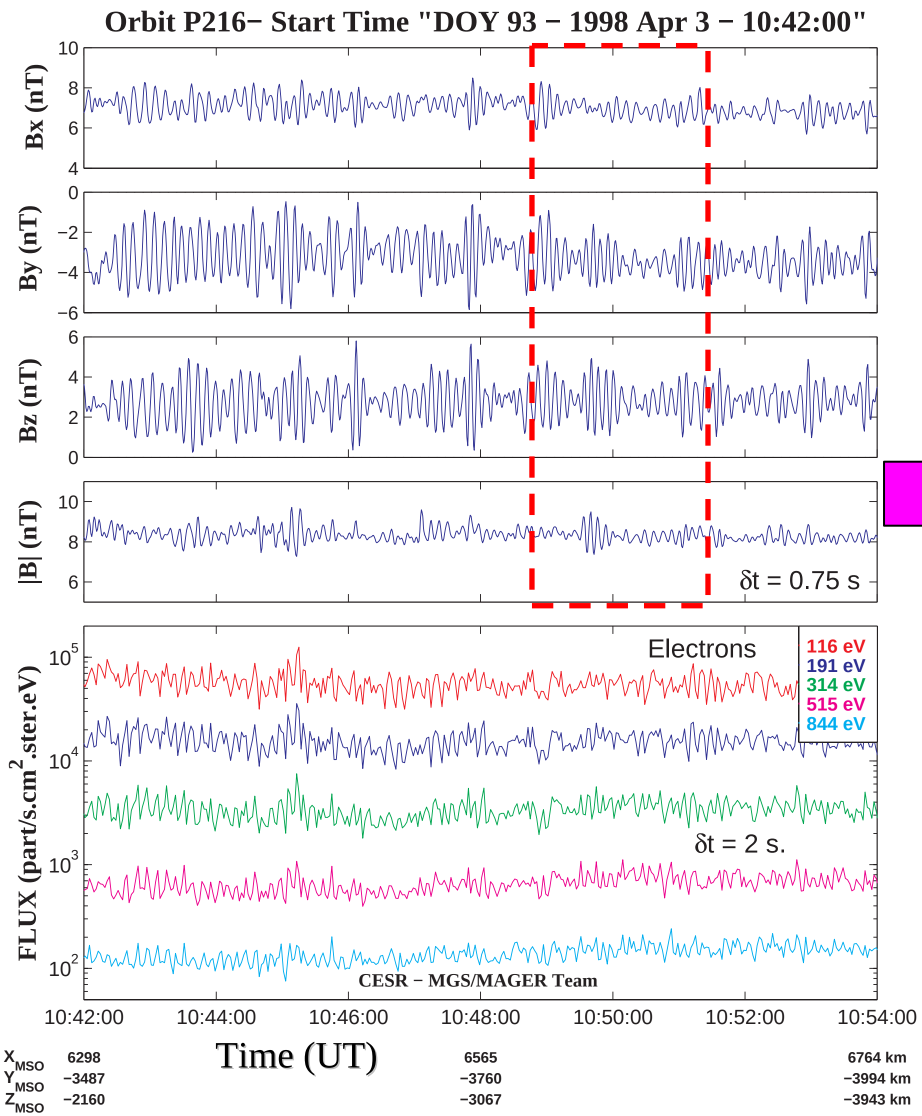
Low frequency coherent waves upstream from the bow shock

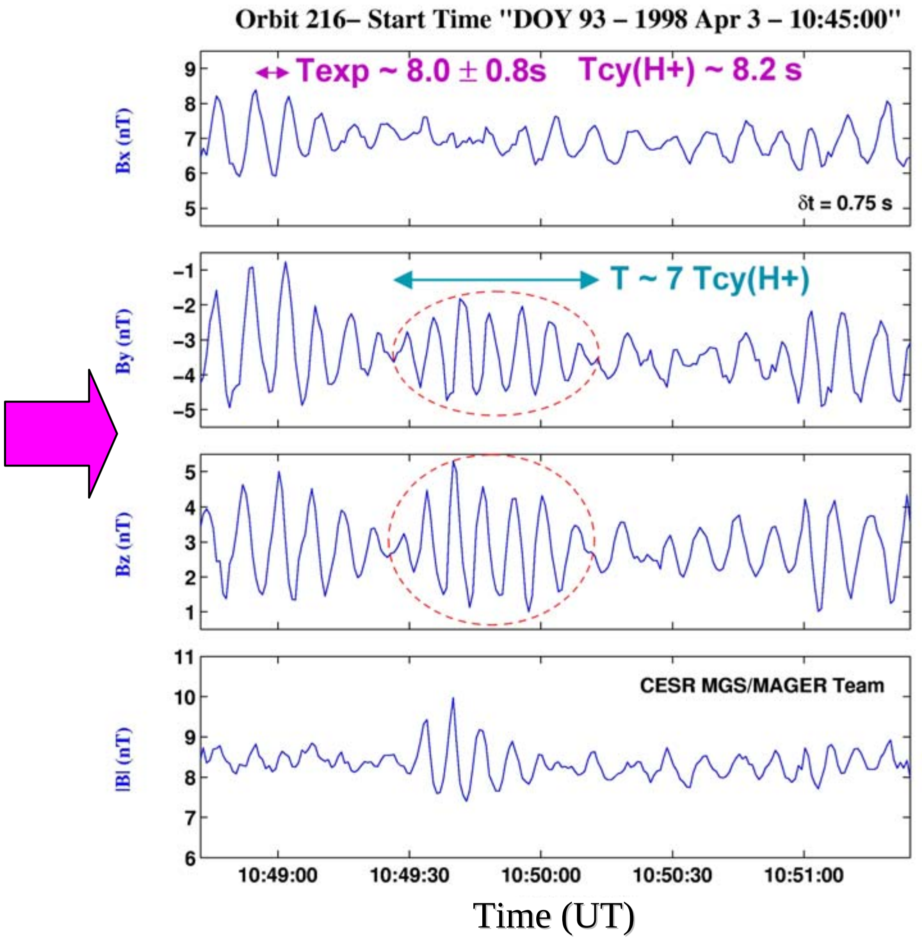


- Observed around the proton cyclotron frequency Ω_p during very long duration (here, more than 3 hrs).



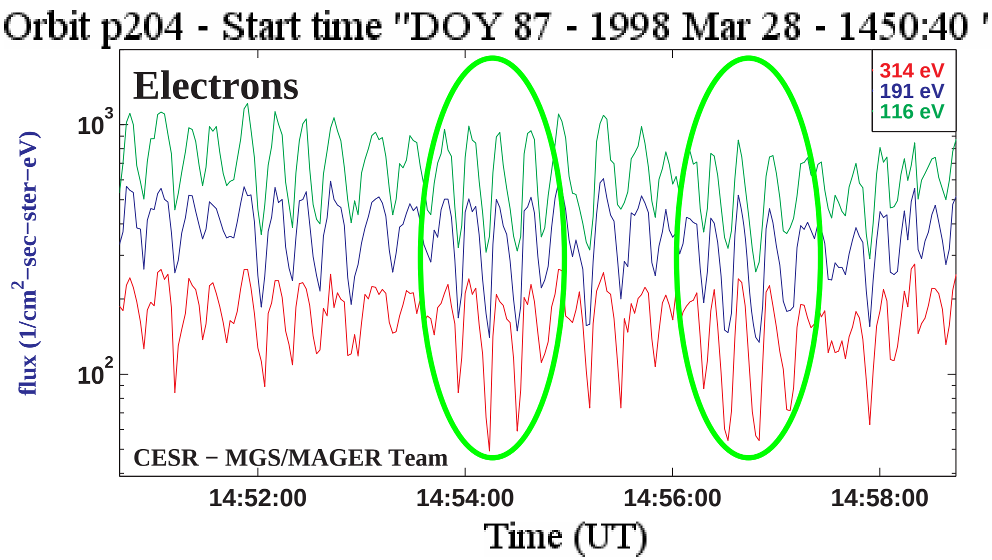
Packet structure of coherent large-amplitude waves at Ω_p





modulation at ~0.1 Ω_p

Coherent waves: particle observations (electrons)



Waves observed on SW electron fluxes for all energy levels (> 10 eV)

Same oscillations on the total electron density.

Oscillation at Ω_p of density n_{ion}

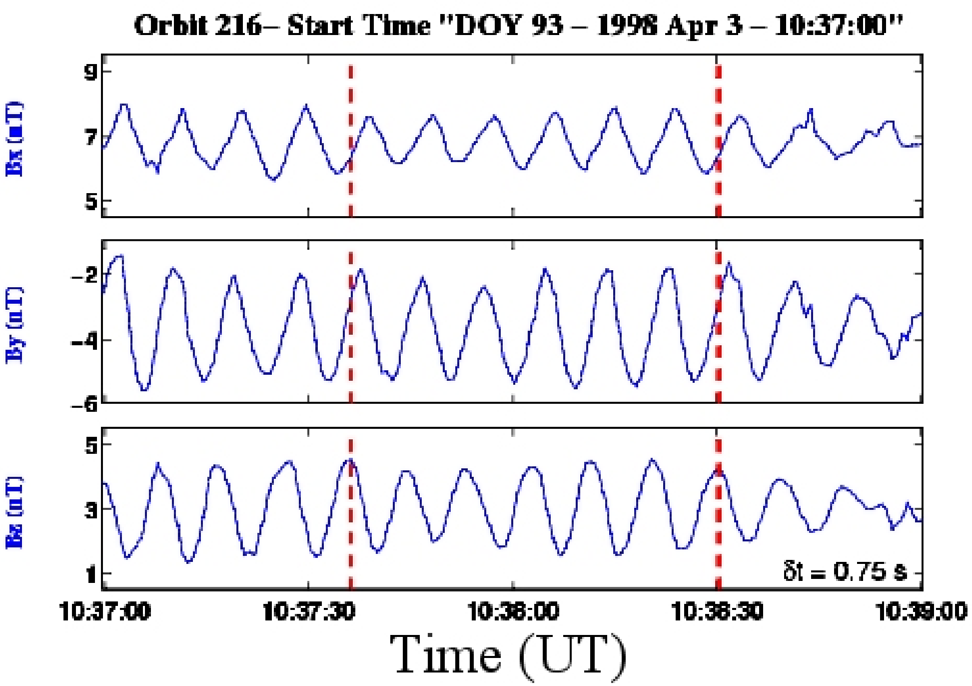
(quasi-neutrality)

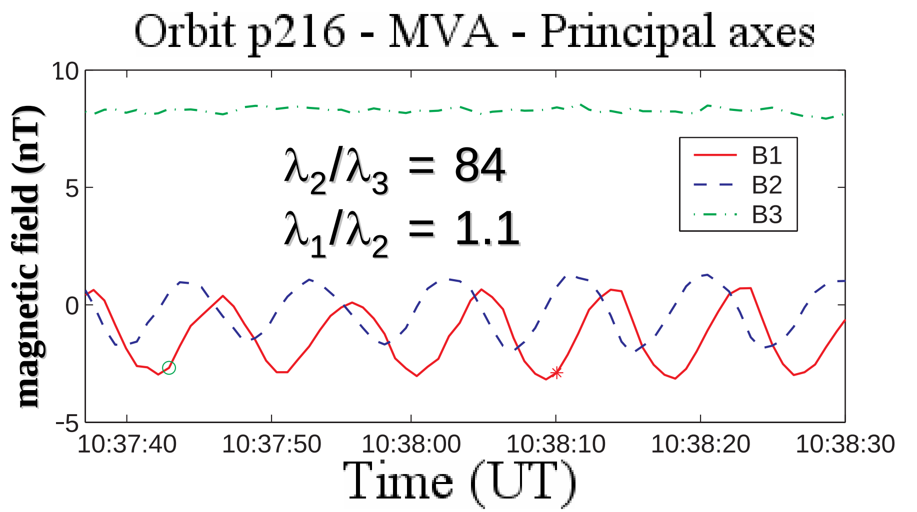
+ anticipated modification of the ion distribution.

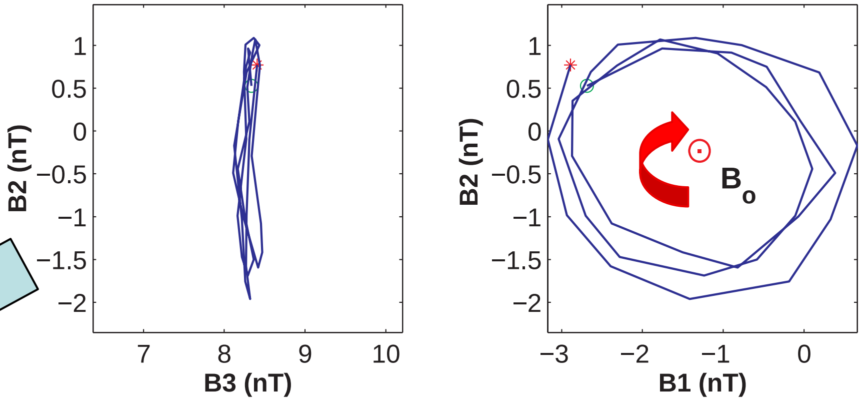
(no ion measurements on MGS)

Polarization Analysis

minimum variance analysis (MVA)







(*Mazelle, Bertucci et al.*, 2004)

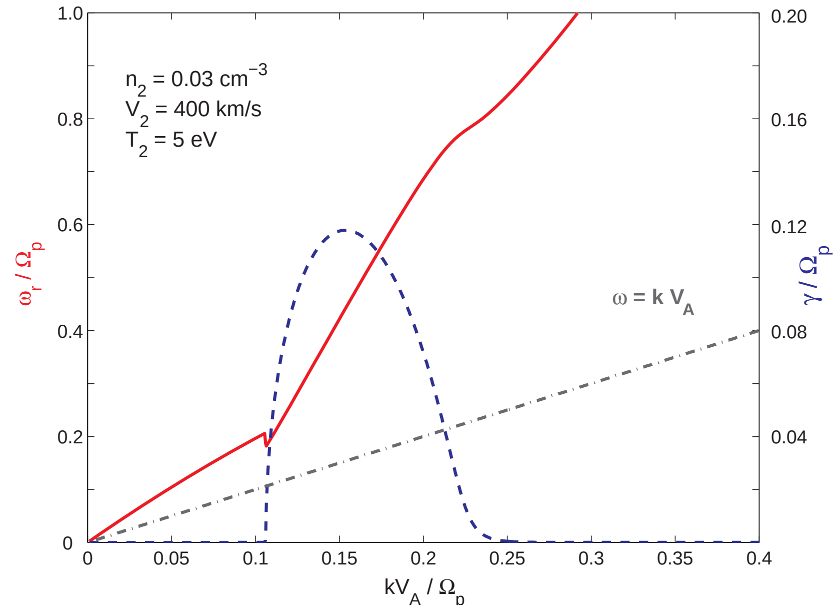
- **Plane waves**
- **θ_{kB} = 9.0 ± 0.7° ⇒ Slightly oblique propagation**
- **Left-hand circular polarization (s/c frame).**
- **Large amplitude ($\delta B/B$ ~ 0.3)**

Wave generation at Ω_p result of linear theory

Resolution of the Maxwell - Vlasov linear dispersion equation

- **2 ion populations:**
  - **Protons (solar wind).**
  - **Implanted Protons (Exosphere)** as a beam.

- Beam temperature < 100 eV.
- Beam density < 1% SW.



Ion/ion right-hand mode driven unstable

Vph < V_{VS} ⇒ Doppler shift ⇒ left-hand polarization + Ω_p in inertial frame (MGS)

How to explain:
- **Coherency?**
- **Packet structure ?**
- **Large amplitude?**

Need for a nonlinear approach

Wave amplitude

- **Large wave amplitude** (up to **5 nT peak-to-peak**) inconsistent with the nonlinear saturation value of proton cyclotron waves [e.g., Convery and Gary, JGR, *102*, 2351, 1997] or to the results of computer simulations for pickup ions [e.g., Gary *et al*., JGR, *94,* 3513*,* 1989] which predict rapid scattering at low saturation level.

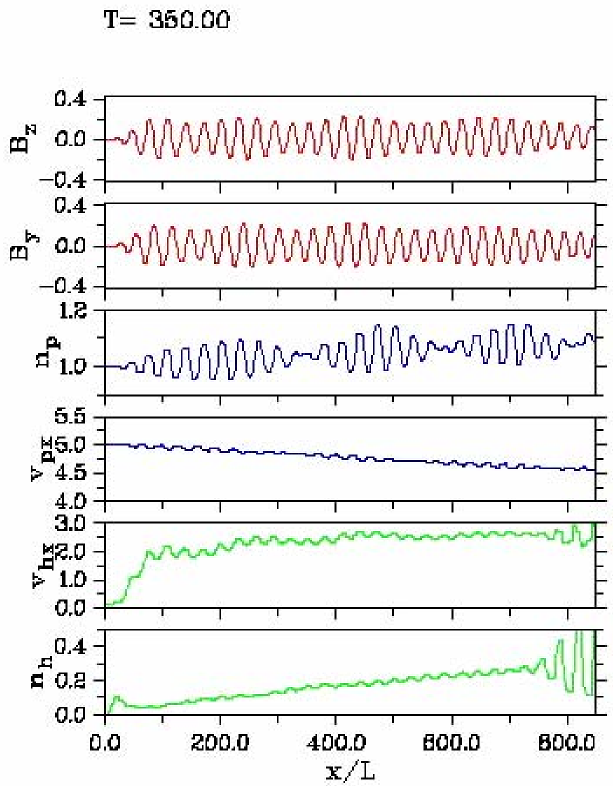
$$\frac{|\delta B|^2}{B_o^2}\Big|theory = \frac{1}{12}\frac{n_{ring}}{n_e}\left(\frac{v_{\perp o}}{v_A}\right)^2 \leq 0.04$$

$$\frac{|\delta B|^2}{B_o^2}\exp = 0.2$$

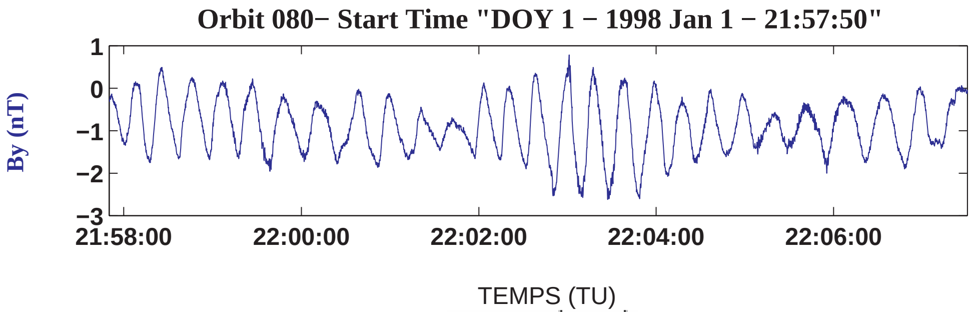
$$n_e = 4cm^{-3},\ V_{\perp 0} = V_{SW} = 400\,km/s,\ n_{ring} = 0.1cm^{-3}$$

Stationary waves in a multi-ionic plasma

<u>Simulation with a proton beam in the solar wind plasma.</u>



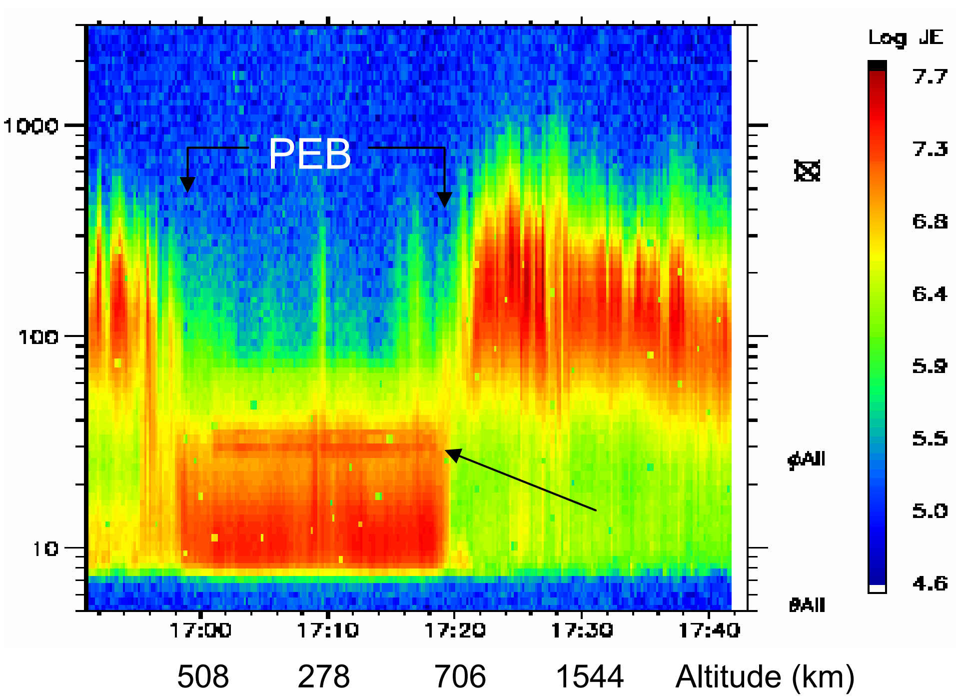
Courtesy K. Sauer

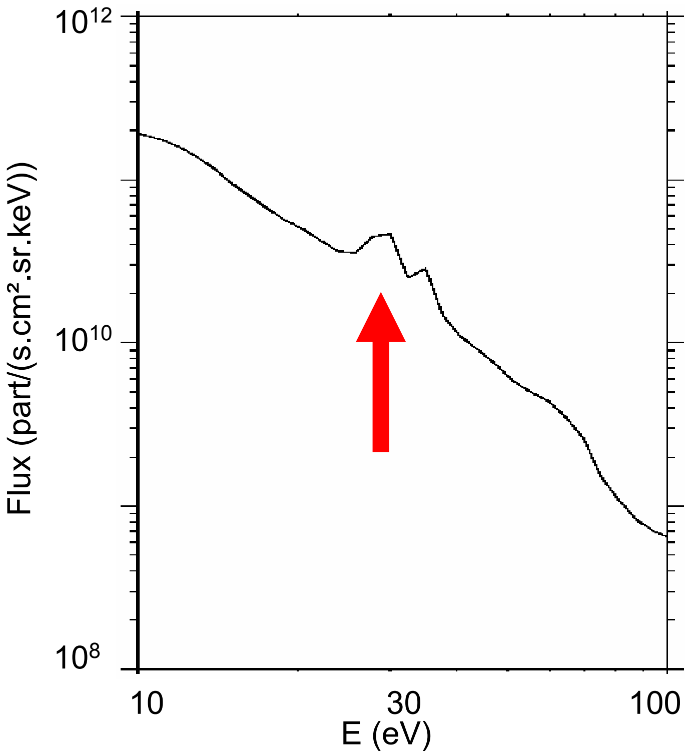


- Such structures are observed in the **inertial frame (~ spacecraft)** as waves with a frequency close to Ω_p.
- They are **circularly** polarized with a **left-hand** polarization in the inertial frame (~ spacecraft).
- In that conditions, the **right-hand mode** is **linearly unstable** (*Sauer and Dubinin*, 2003).

PEB : PhotoElectron Boundary

- A boundary first reported from MGS data (electron flux drop-out at E > 100 eV).
- A new criterion (MEX): a clear photo chemical signature



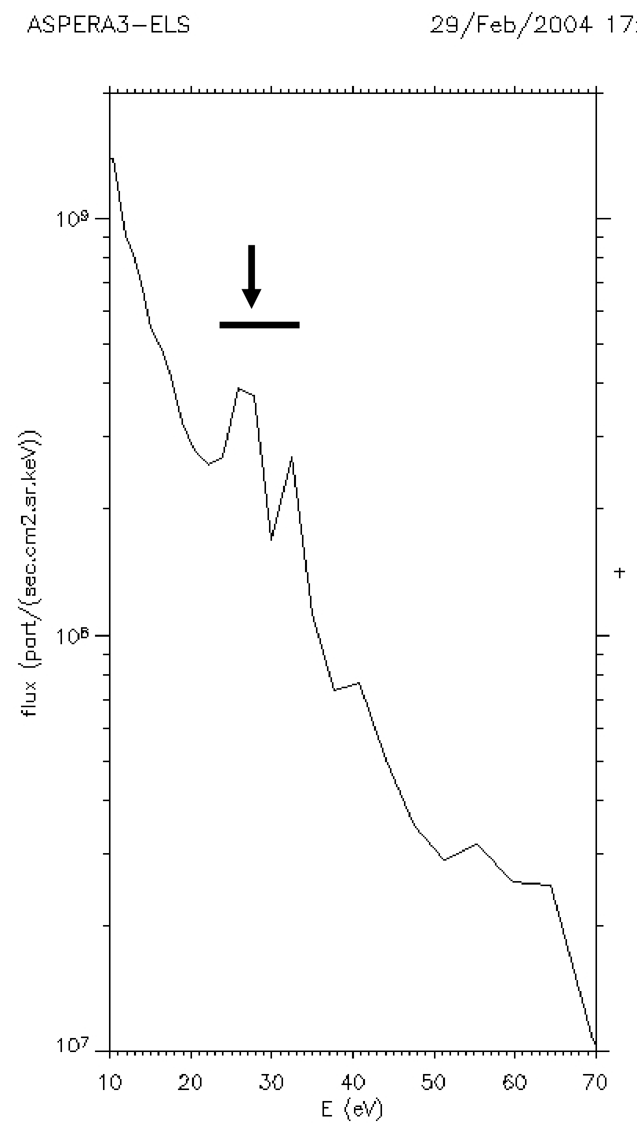


Photochemical electron peaks

- Systematical detection of spectral peaks in the ionosphere.

- - suddenly disappear at the PEB

  - electron fluxes are almost independent of altitude



MARTIAN PHOTO-ELECTRONS ESCAPE

Mars Express

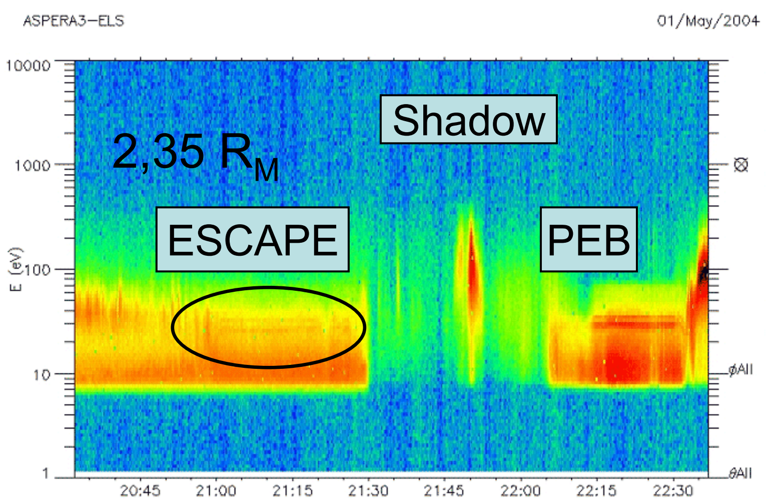
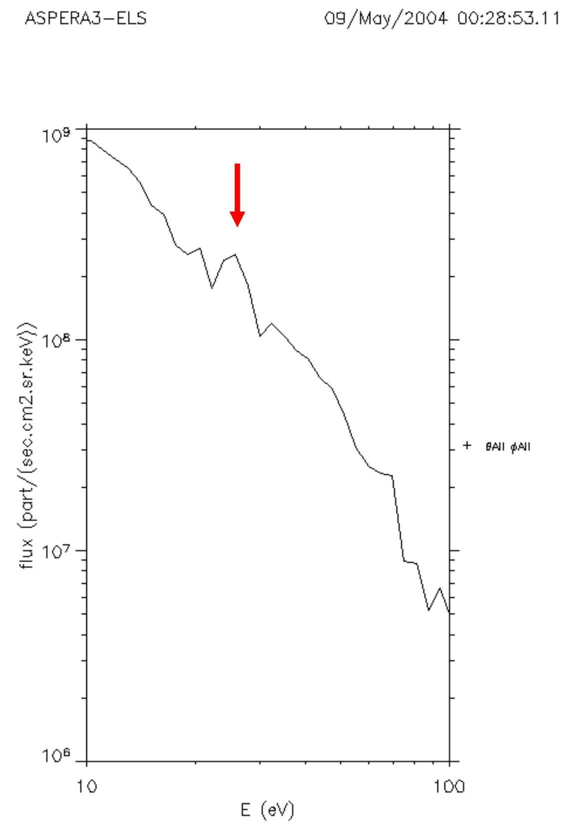
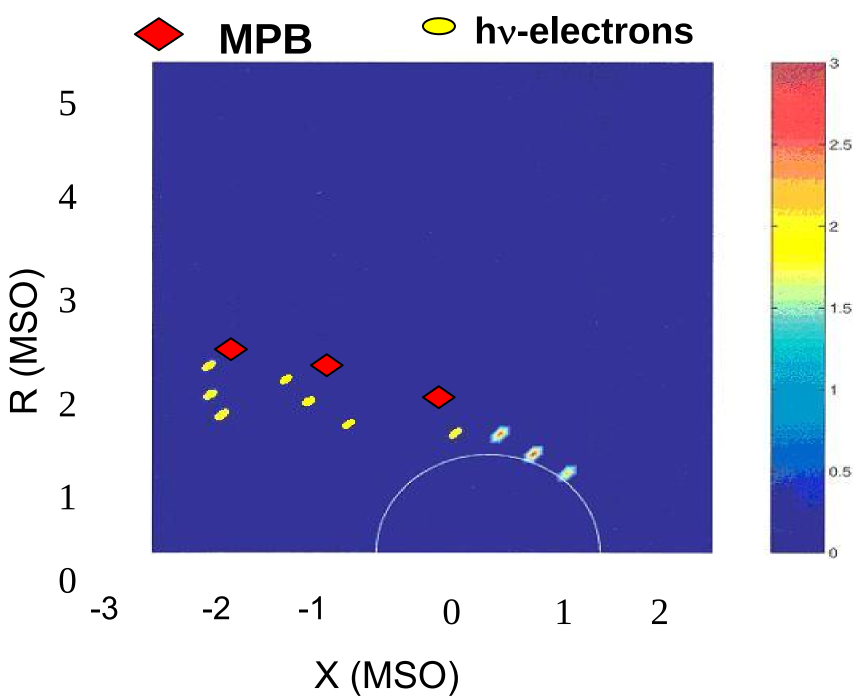


Photo-ionization of CO_2 by solar hν @ 304 Å





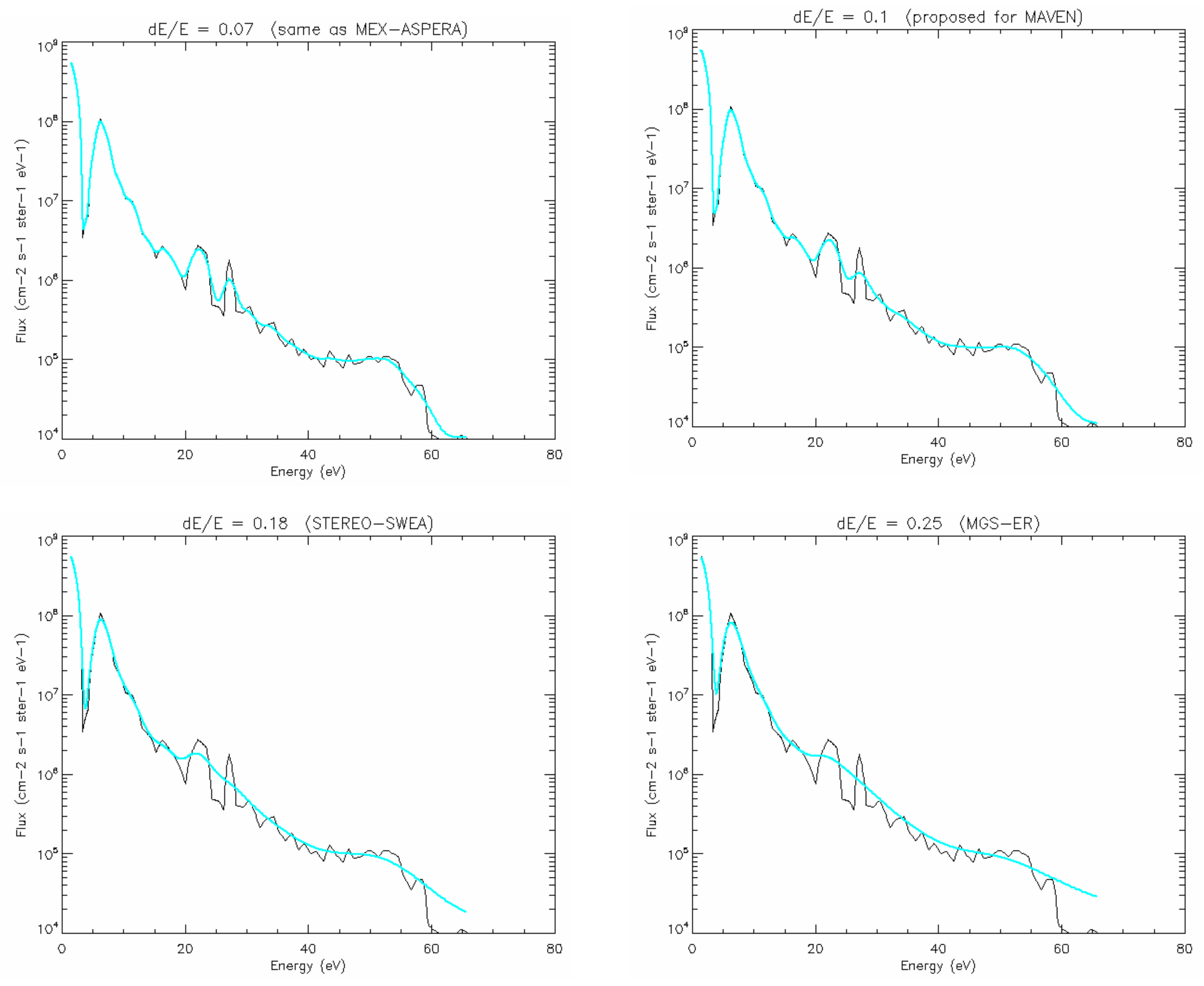
Escape associated to heavy ions

(M> 16)

Mars: escaping photoelectrons

- The maximum production rate of photoelectrons in the 20-30 eV range (304 Å) occur at altitudes of the order of 170-200 km, vertical transport is then predominant.
- Photoelectrons escape along the magnetic field to reach the antisolar and flank regions located between the PEB and the MPB.
- Electrons with energies lower and higher than those of the CO_2 peaks also escape.
- The plasma neutrality (ambipolar E) requires the loss of (10) tons of ions/days: a planetary wind

Resolving Photoelectron peaks



New ISSI team

Comparative Study of Induced Magnetospheres
(Mars, Venus, Titan, Comets)

Leader: César Bertucci (IAFE, Buenos Aires, Argentina)
Co-Leaders: Ronan Modolo (LATMOS)
and Christian Mazelle (CESR)

First meeting in April 2010 (2 year-duration)