The Mars-solar wind interaction

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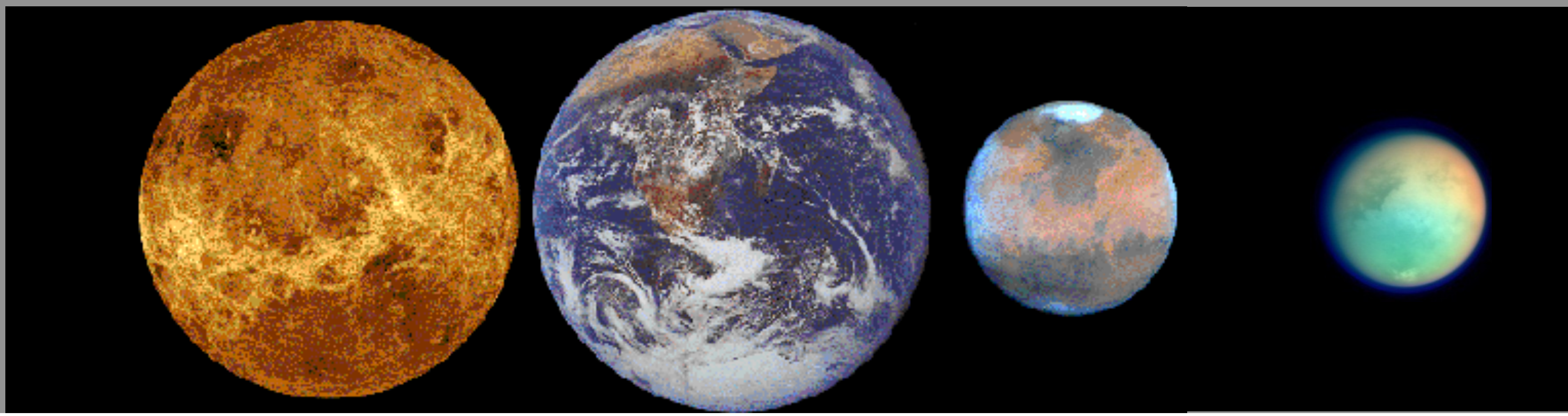
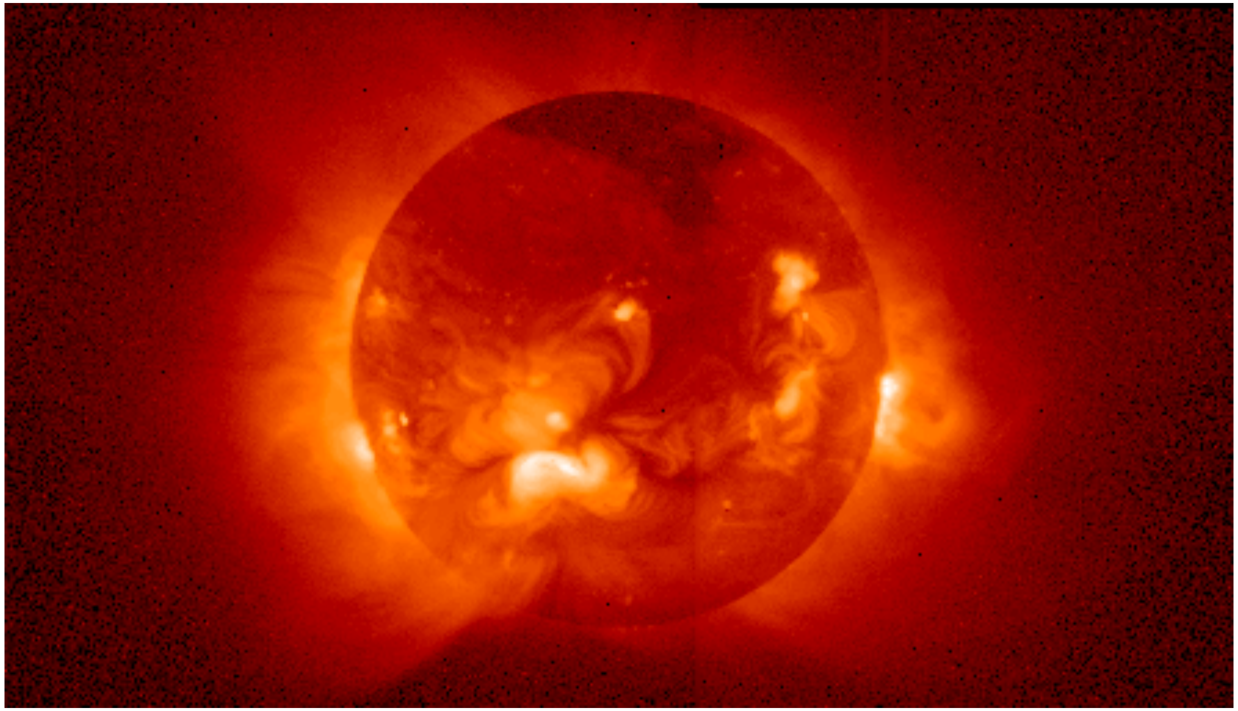
With thanks to O.Witasse, ESTEC for some slides



Mars-solar wind interaction

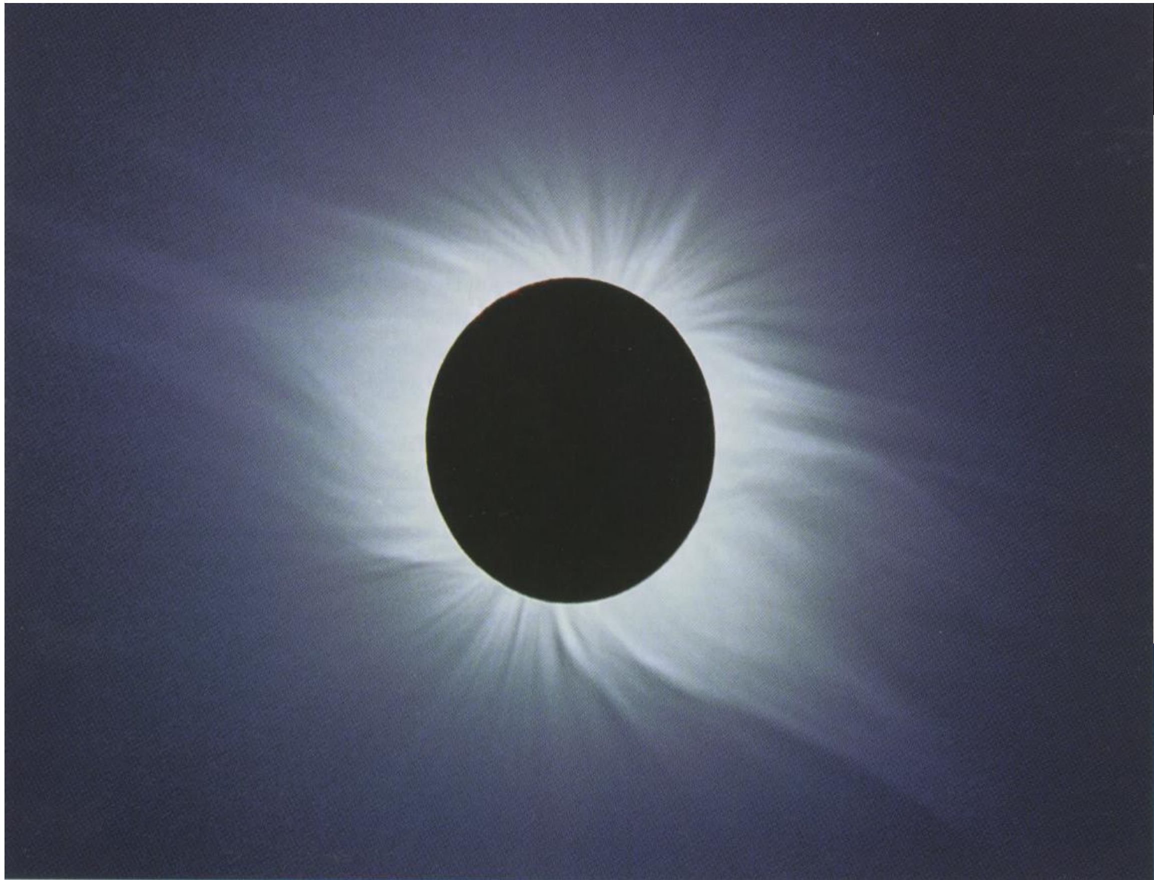
- Solar wind at Mars
- Crustal magnetic fields
- Upper exosphere
- Solar wind interaction region
  - Bow shock
  - Induced magnetosphere boundary
  - Photoelectron boundary
- Measurements from space missions

X-Ray Image of the Sun



The million degree coronal plasma is source of ionizing photons and also the solar wind.

Our Sun – magnetic star



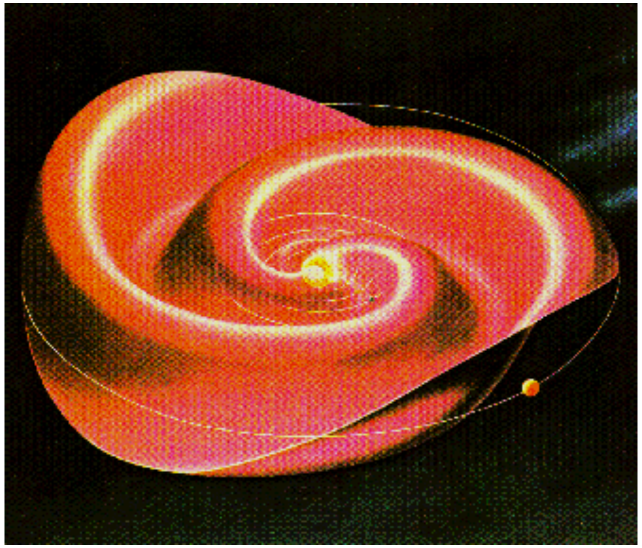
February
1998

August 1999

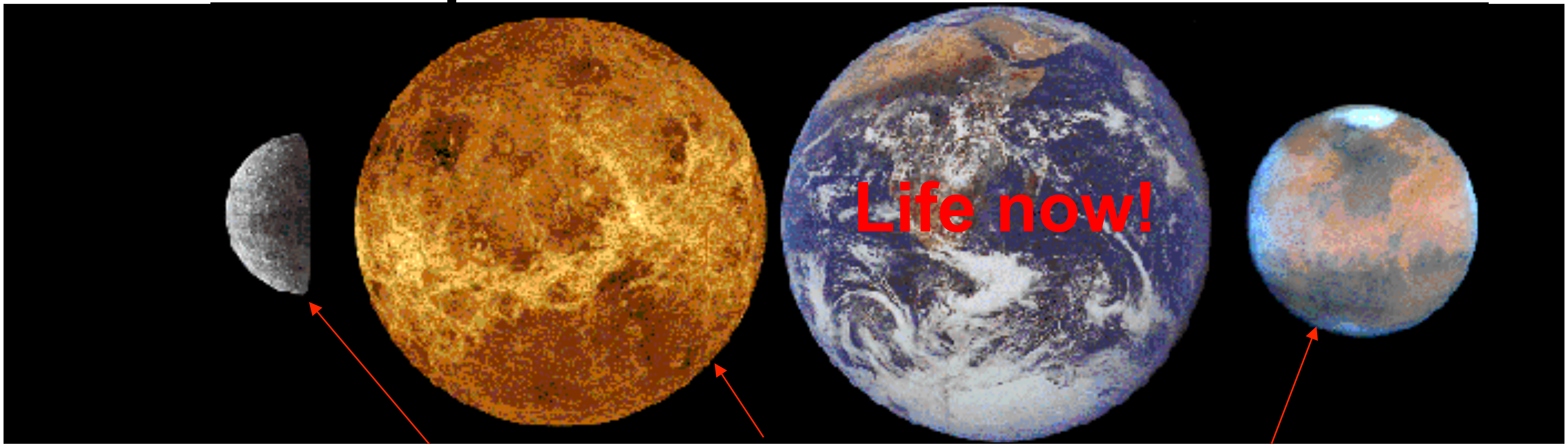
The Solar Wind

- Extension of the solar corona
- Frozen-in solar corona composition (mostly protons and alpha particles; 0.1% heavy ions - C, N, O, Si, S, Fe,….)
- At 1 AU, average solar wind properties:

  $n \approx 7\ cm^{-3}$, $u \approx 400$ km/s, $T \approx 10$ eV, Mach number $M \approx 10$, $B \approx 10$ nT.
- Slow and fast speed solar wind streams.

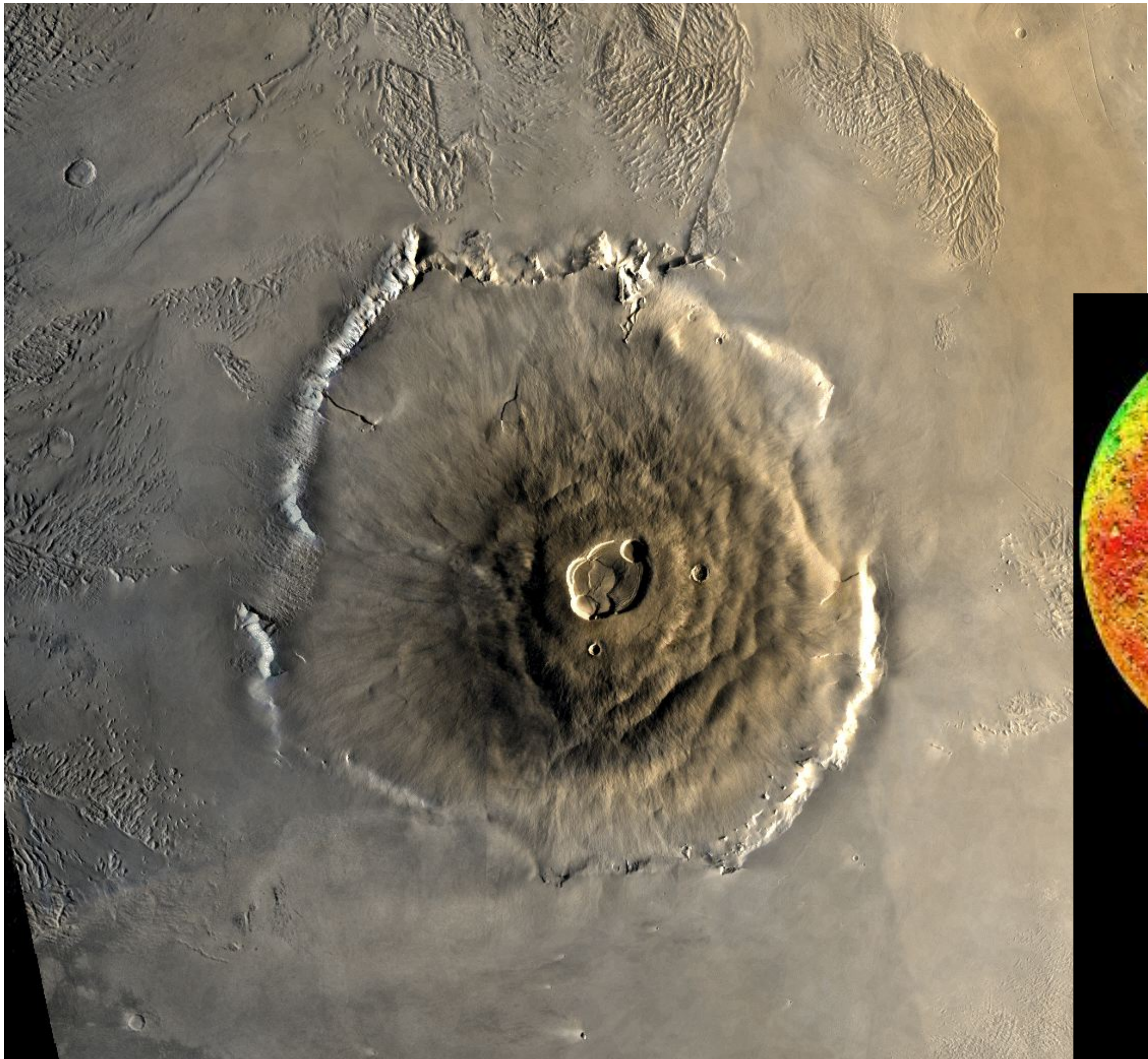


The inner planets



Planet (Earth=1)	Mercury	Venus	Mars
Radius	0.38	0.95	0.53
Orbit	0.31-0.47	0.72	1.52
Atmosphere	No	90 (CO_2)	0.01 (CO_2)
Magnetized	Yes	No	No
Life?	No	No	3.8by ago?
Missions	Bepi-Colombo (2013)	Venus Express (2005)	Mars Express (now)

Mars 3.8 by ago - volcanism

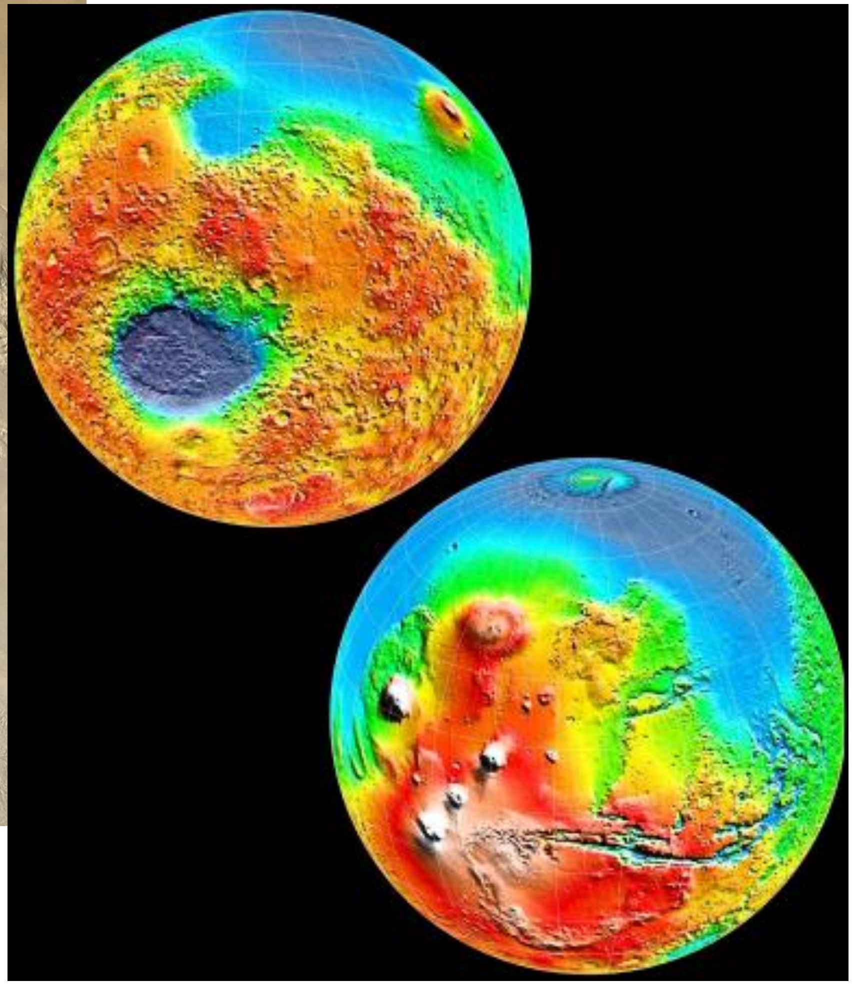


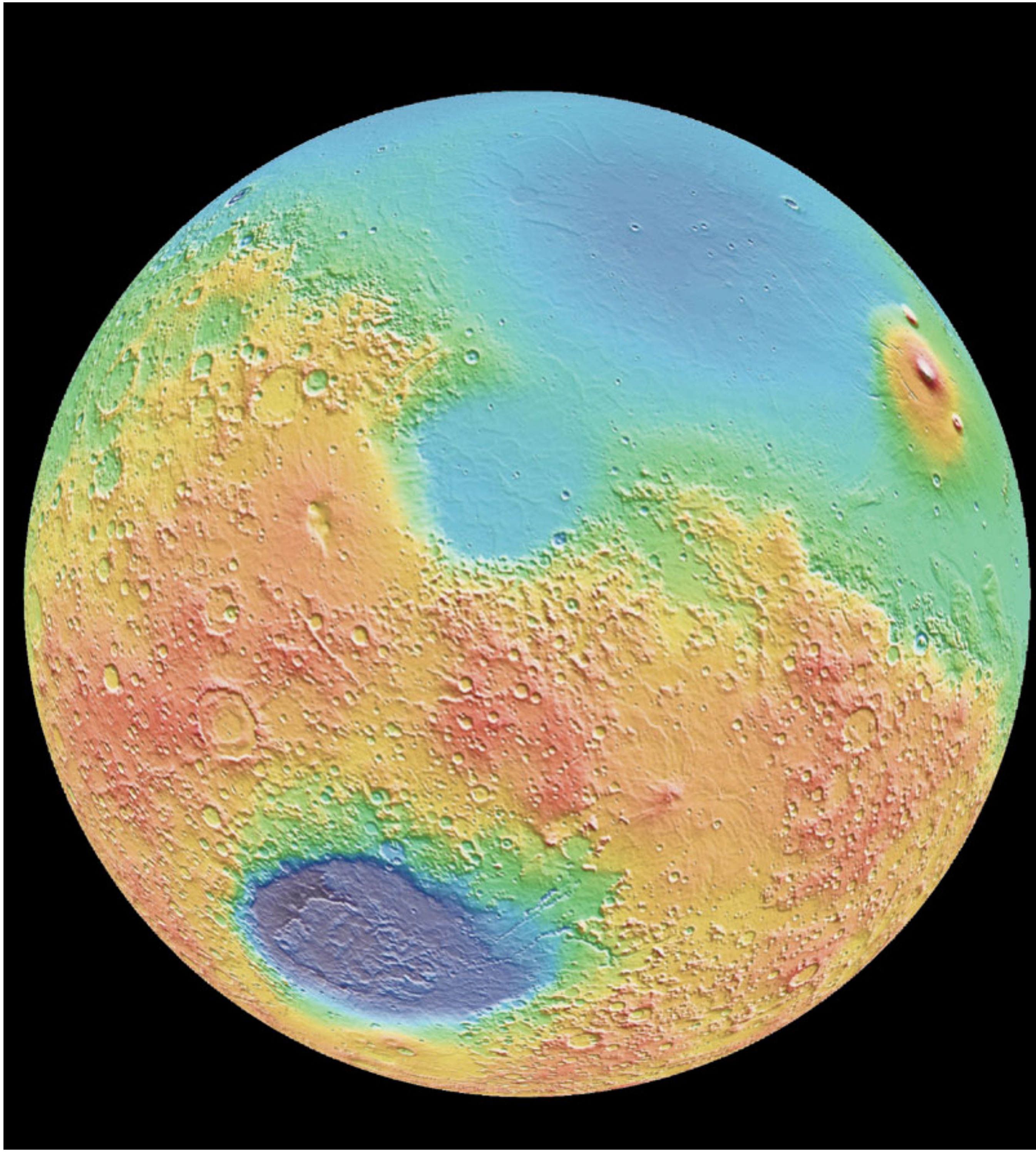
Olympus Mons

600 km diameter

27 km high

Extinct!

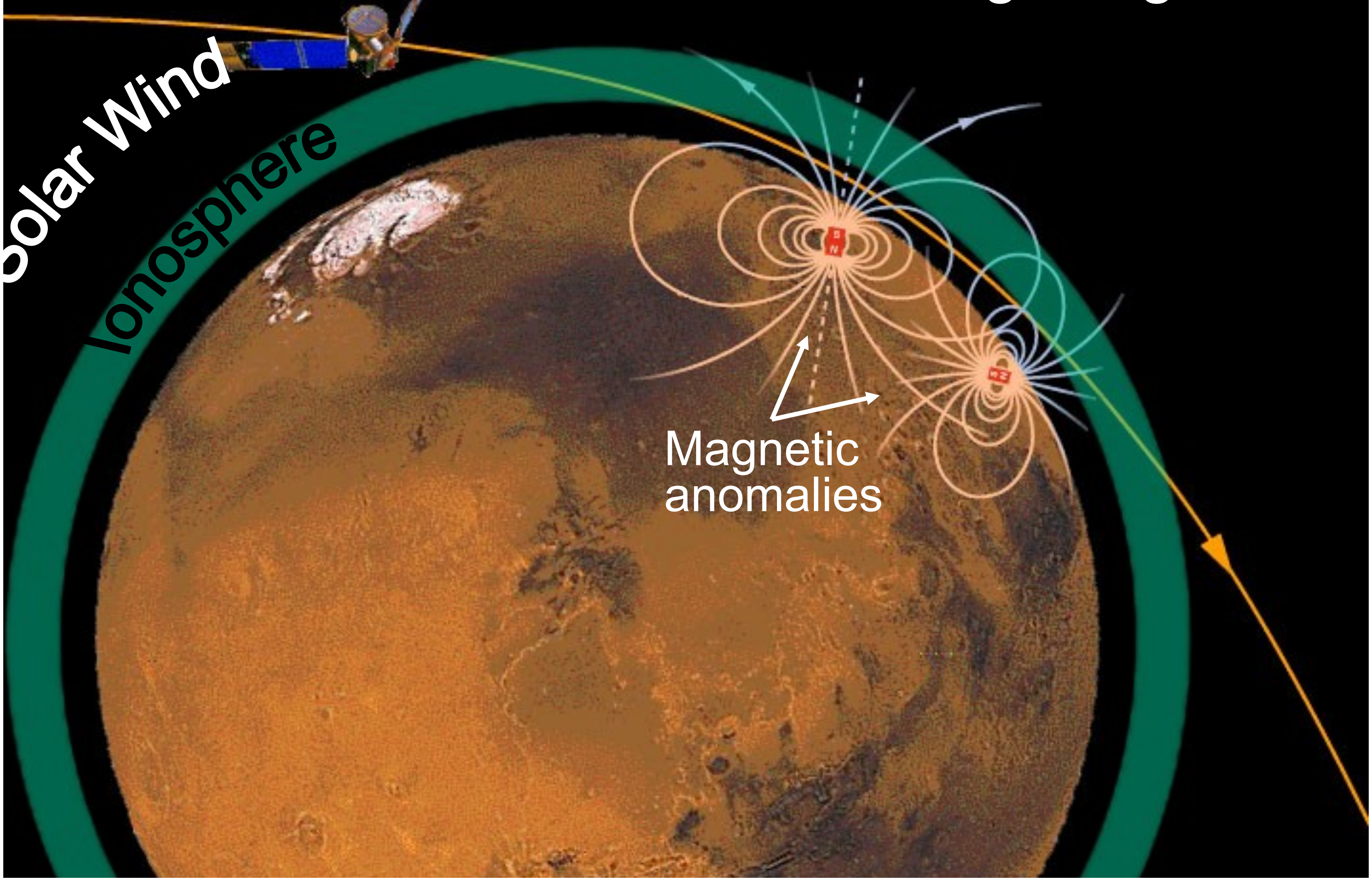




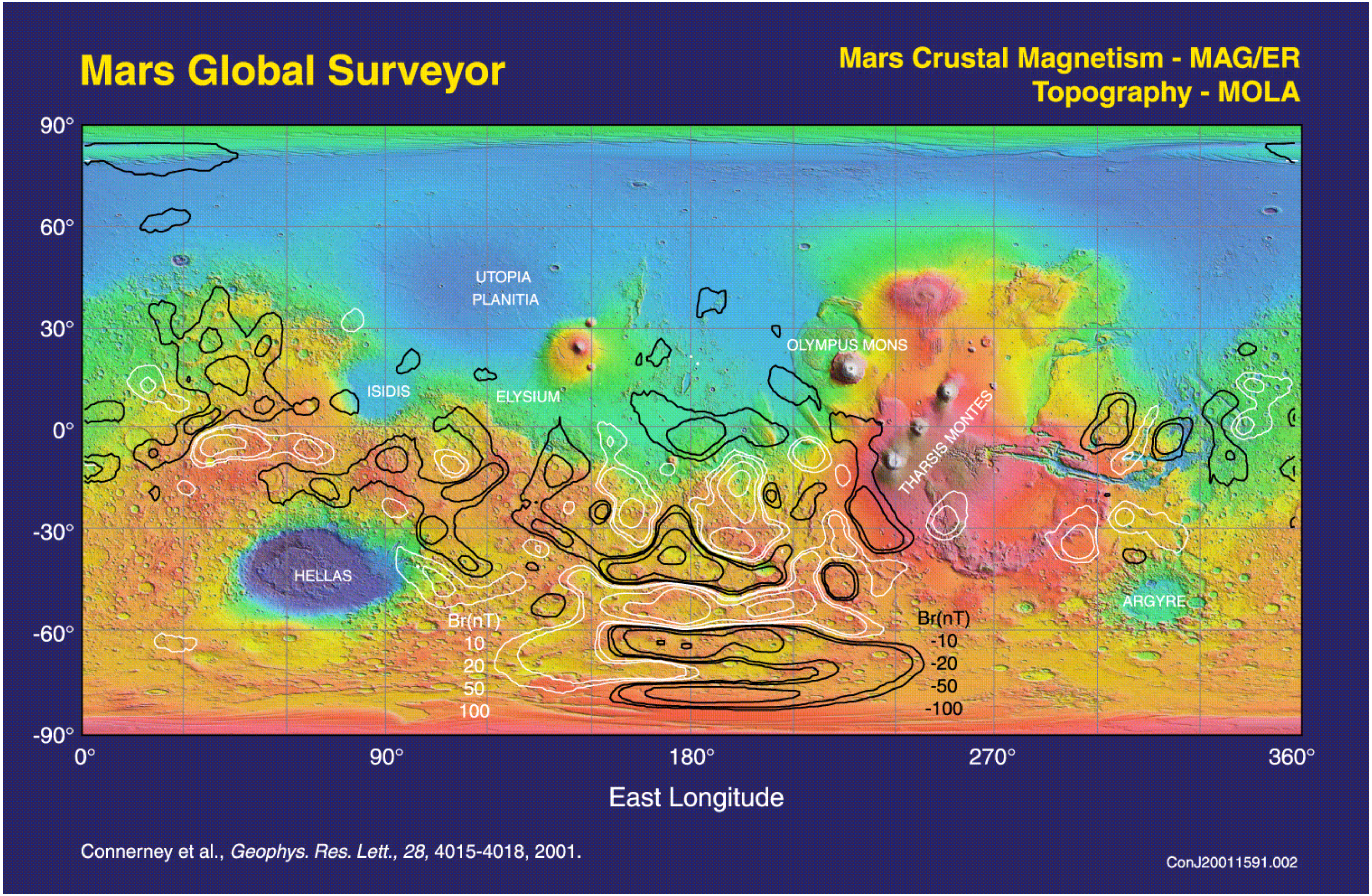
Nature 26/6/08:

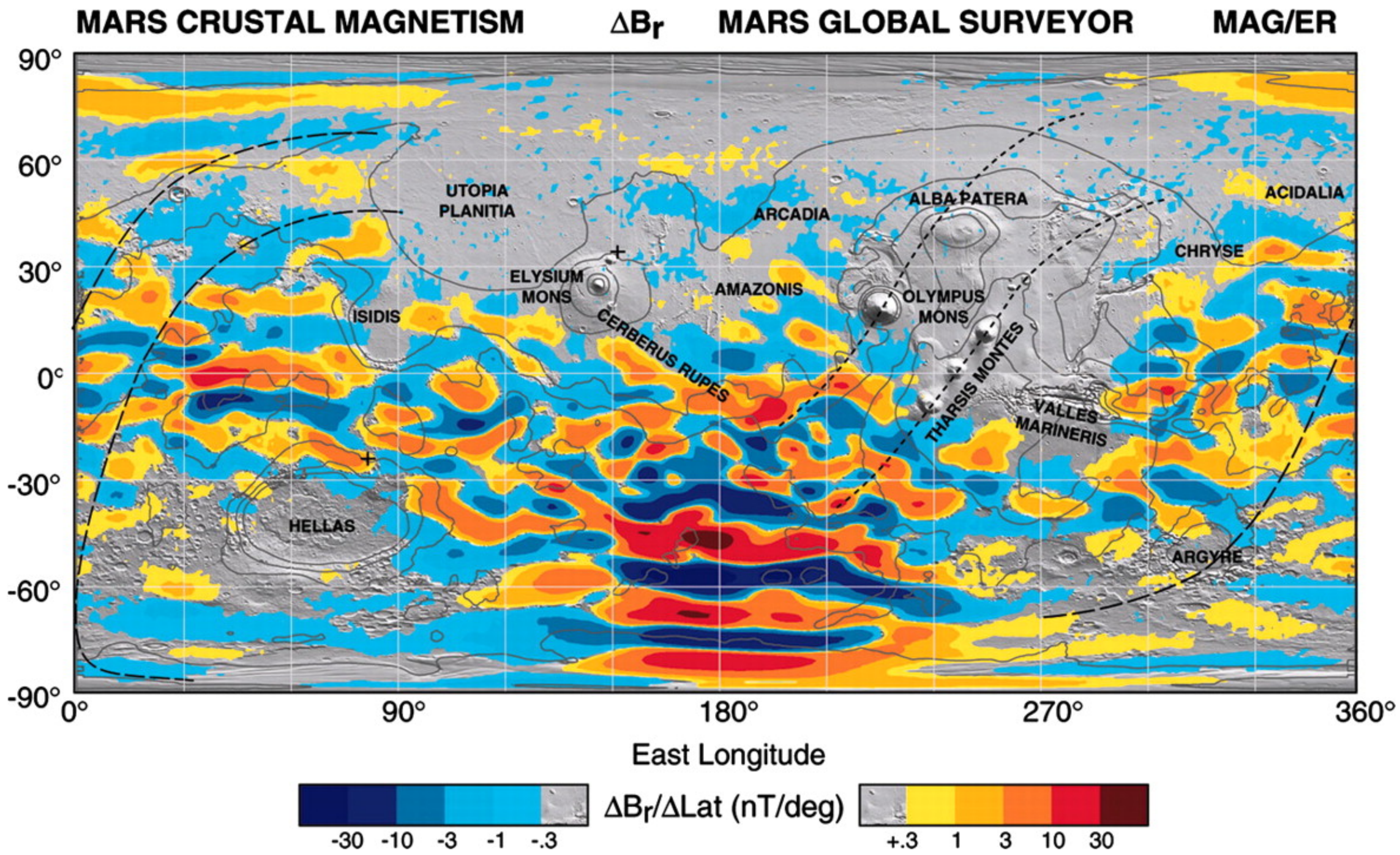
evidence that a large impact caused Mars North-South dichotomy

MGS Aerobraking Drag Pass



Mars 3.8 by ago – large scale magnetic field





Connerney, J. E. P. et al. (2005) Proc. Natl. Acad. Sci. USA 102, 14970-14975

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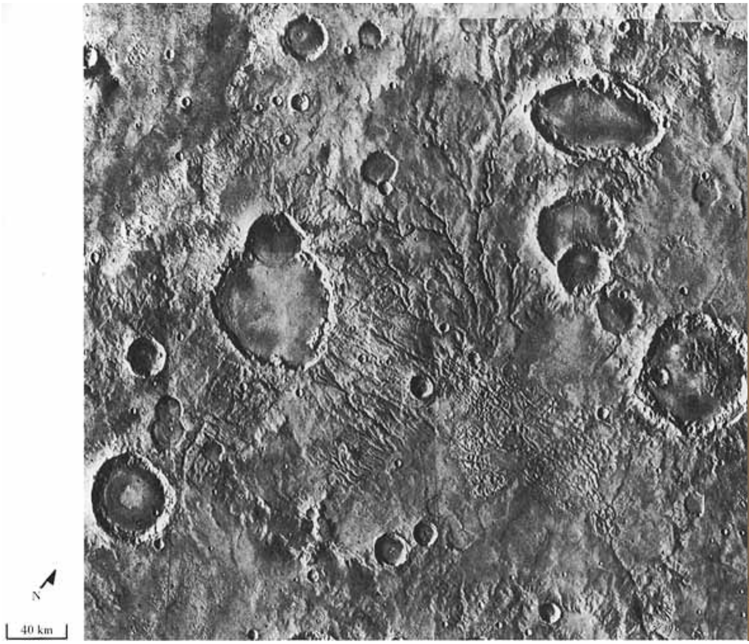
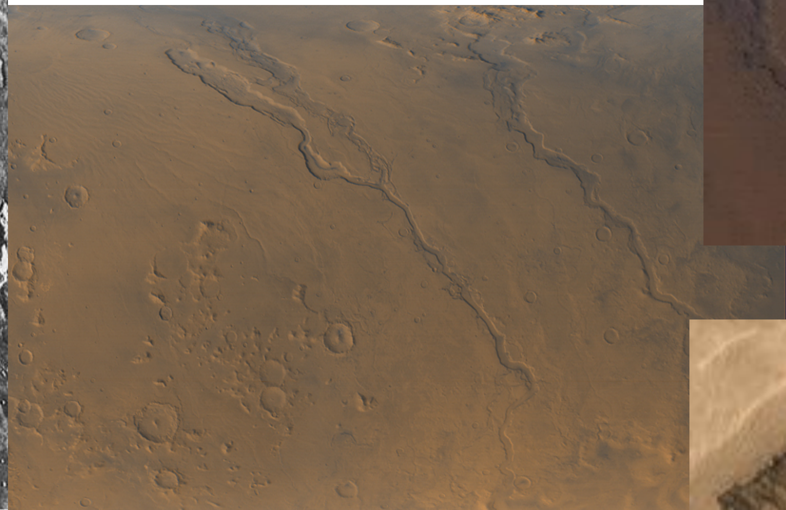
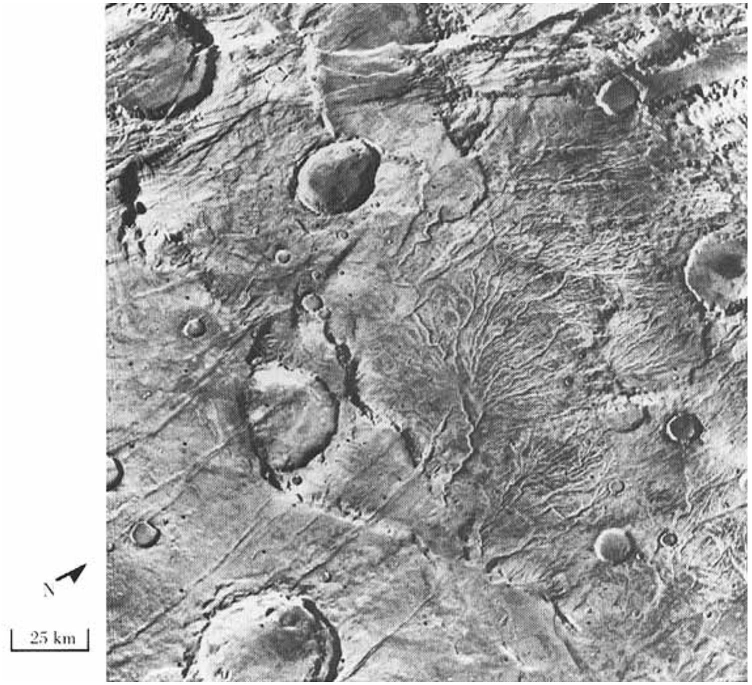
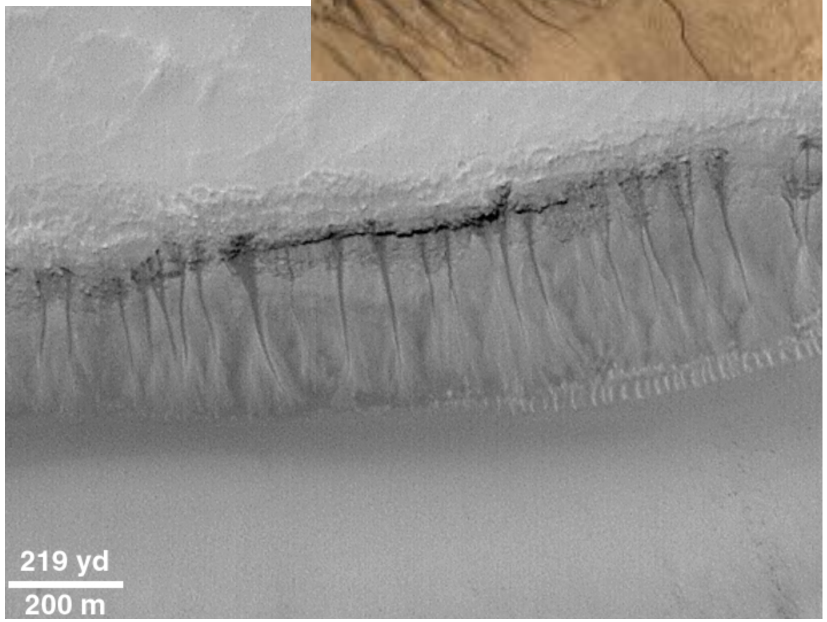






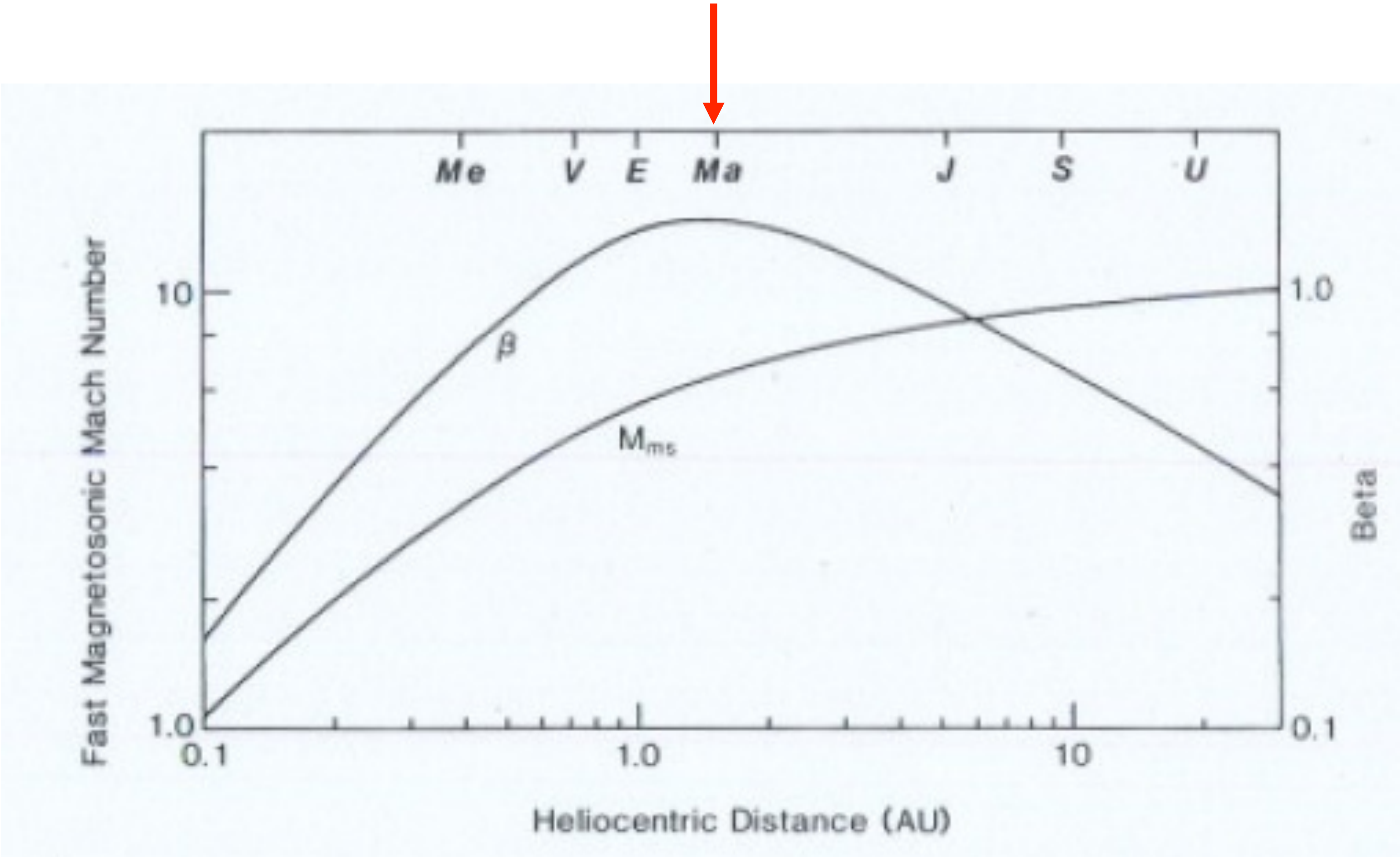
…water seepage within last million years?



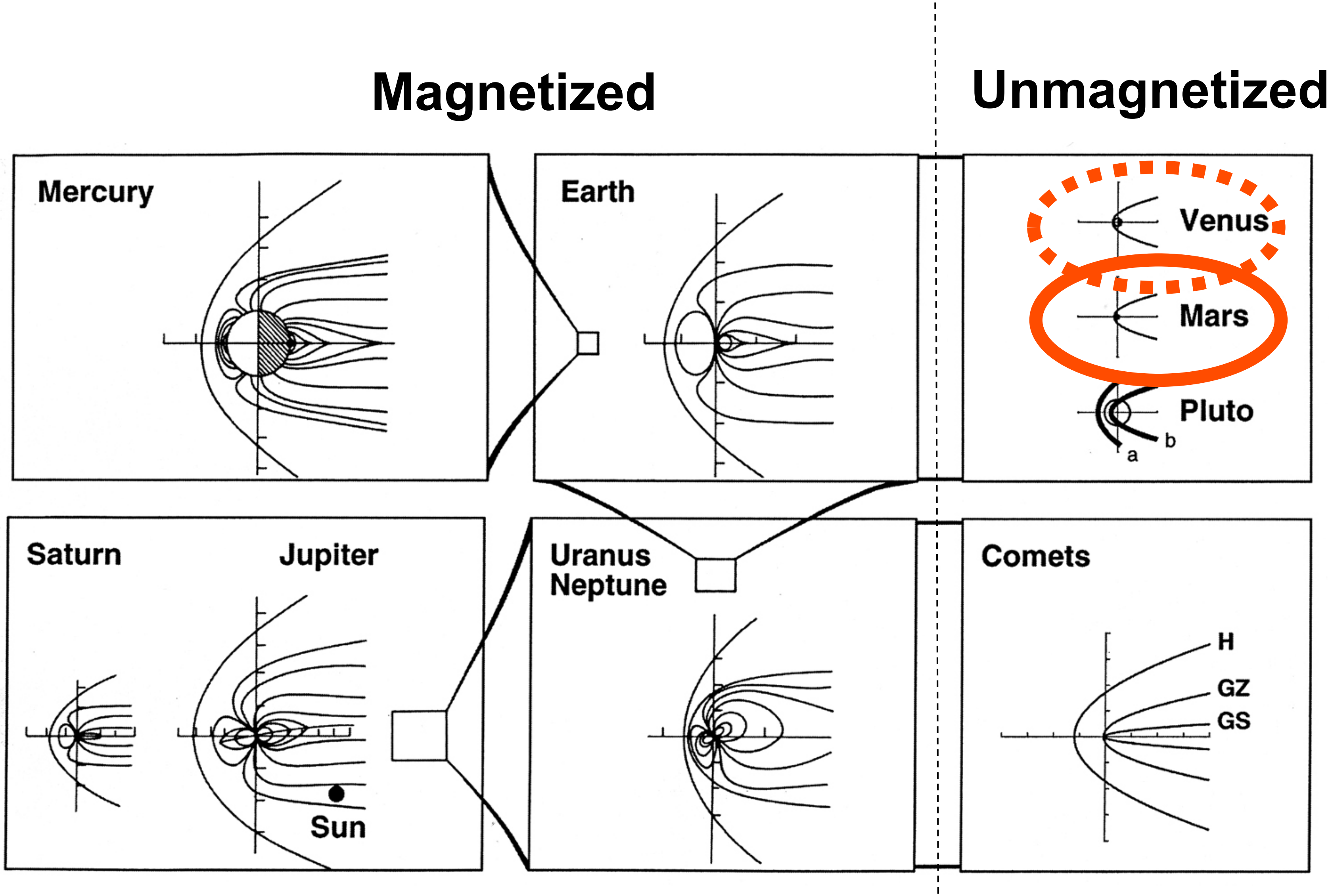
Mars now

- Extinct volcanoes
- No large-scale magnetic field, only remanent regions
- 7 mbar, CO_2-rich atmosphere
- Cold, dry

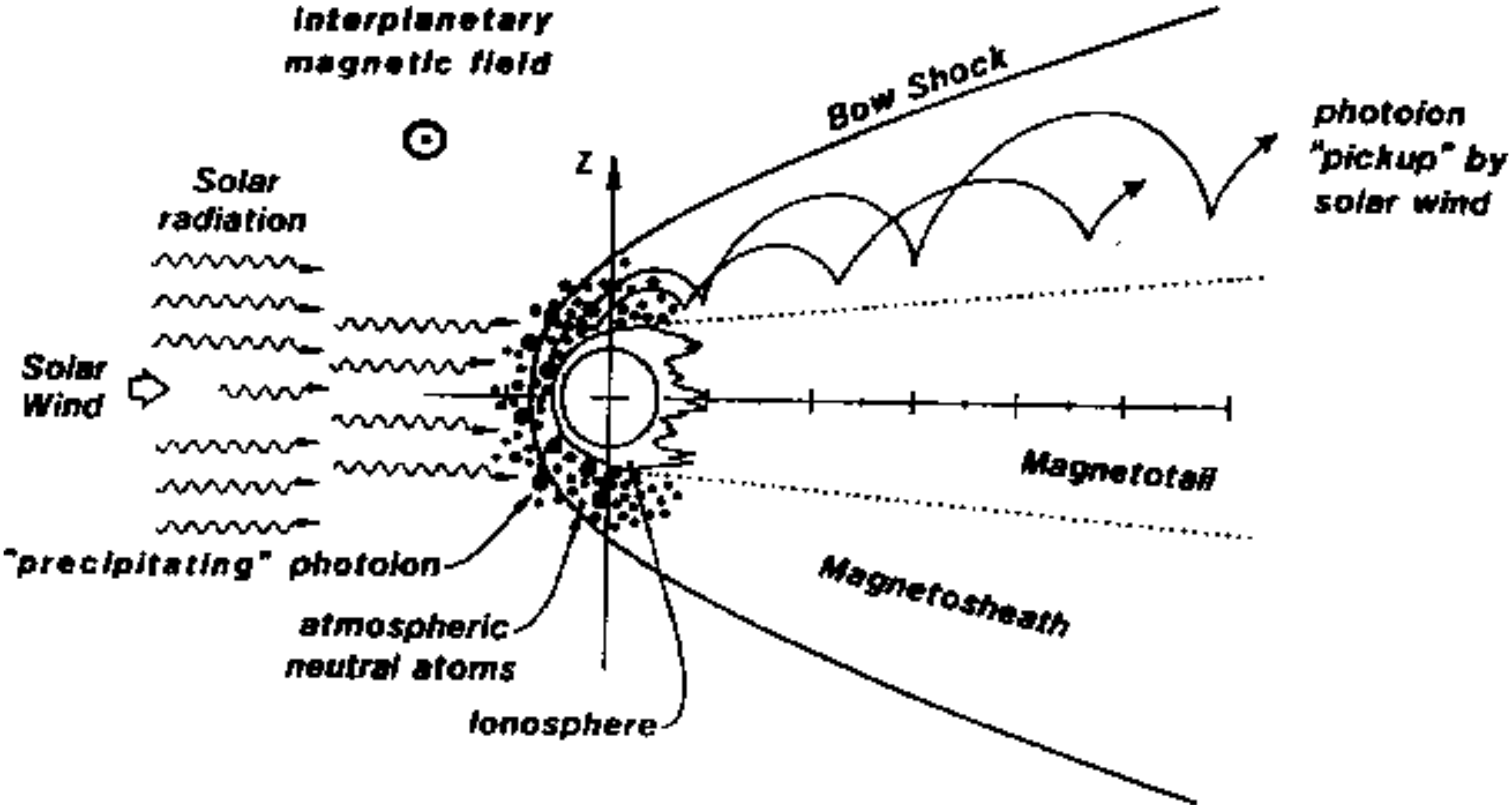
Mars plasma environment



Solar wind interactions in the solar system



Adapted from Coates 2002, Russell and Walker 1995



Mars' atmospheric particles become charged and are pulled away by solar wind, spiralling around the magnetic field – like a comet's tail

Mars crustal magnetic fields: a complex obstacle to the solar wind

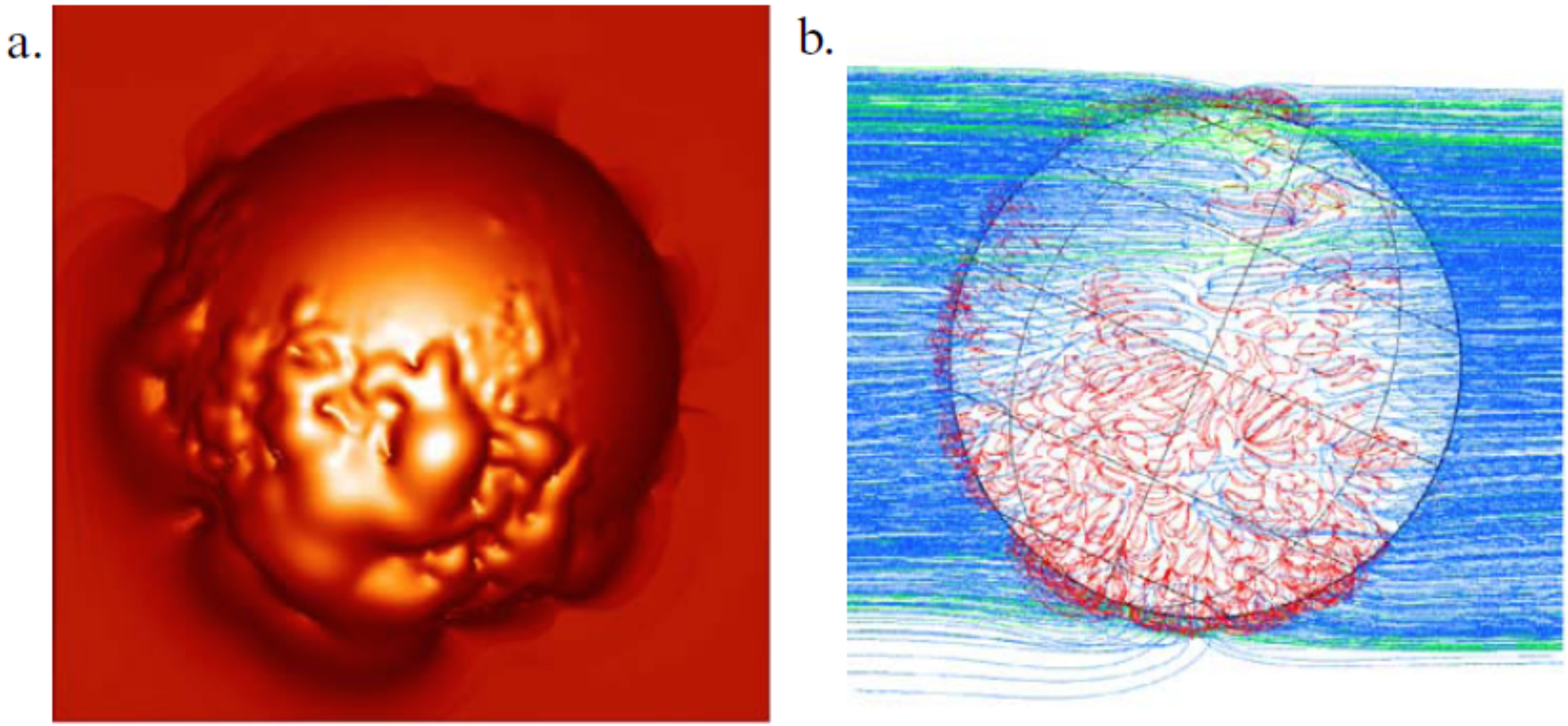


Figure 5. Cartoon showing: (a) the Martian pressure balance obstacle and (b) magnetic field topology. (a) The shape of the Martian solar wind obstacle is derived from a calculation of pressure balance between upstream solar wind dynamic pressure and a combination of ionospheric thermal pressure and magnetic pressure from crustal fields. (b) The magnetic field topology results from field line tracing in a vacuum superposition of a crustal field model with a uniform background magnetic field. Field lines are colored according to their topology: closed (red), open (blue), or draped (green). Mars has the same orientation in both panels. From Brain (2002).

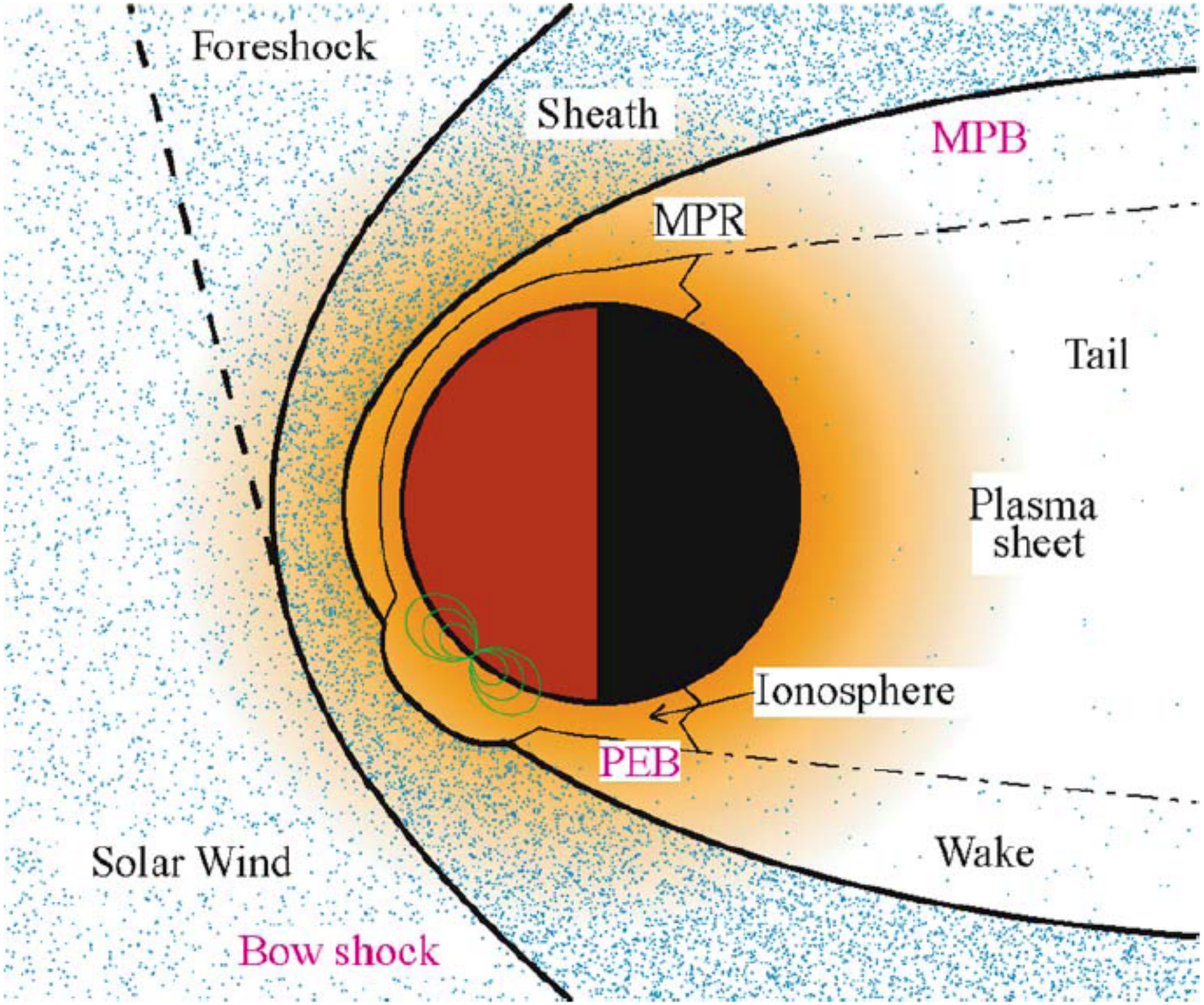
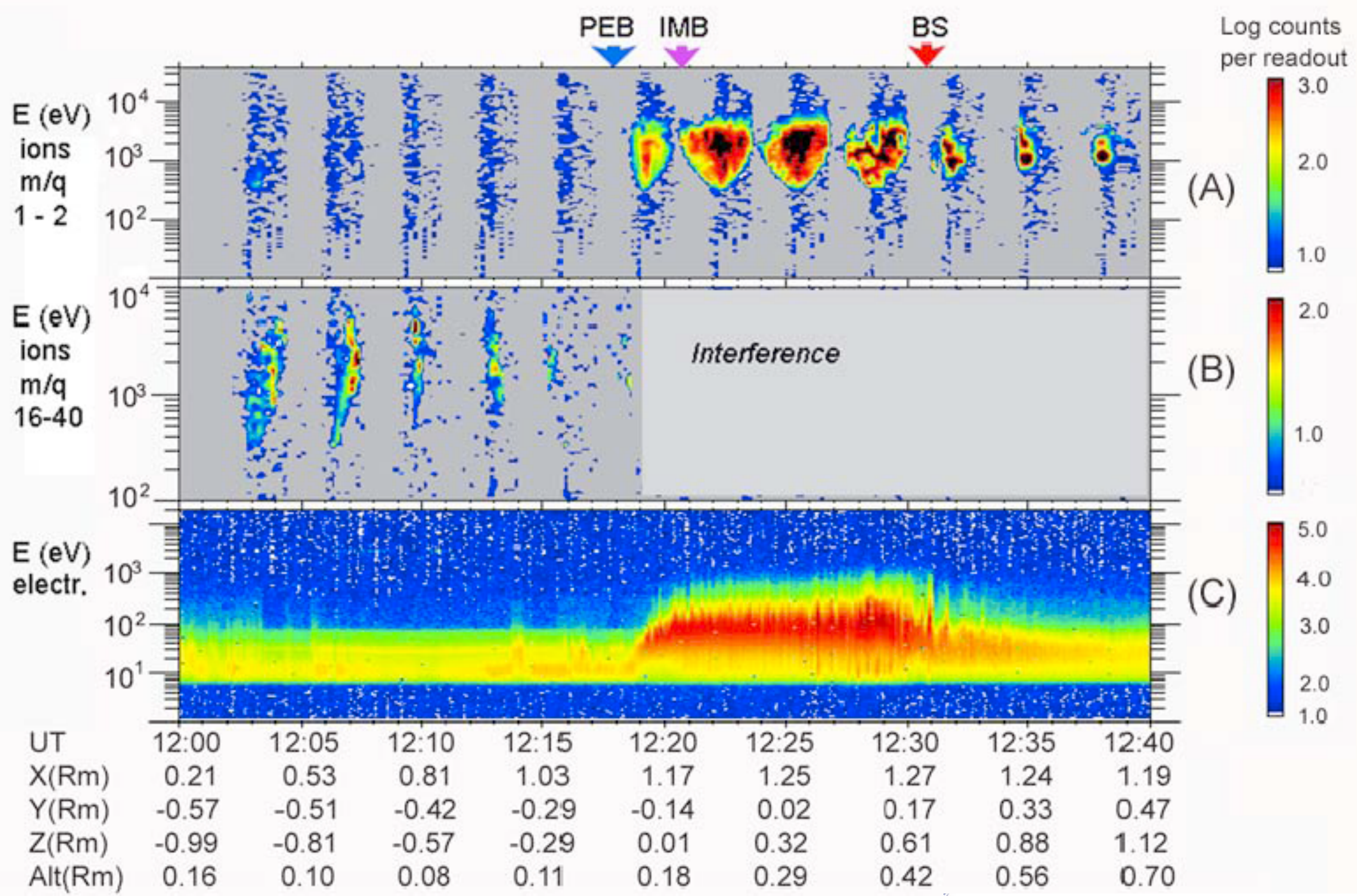
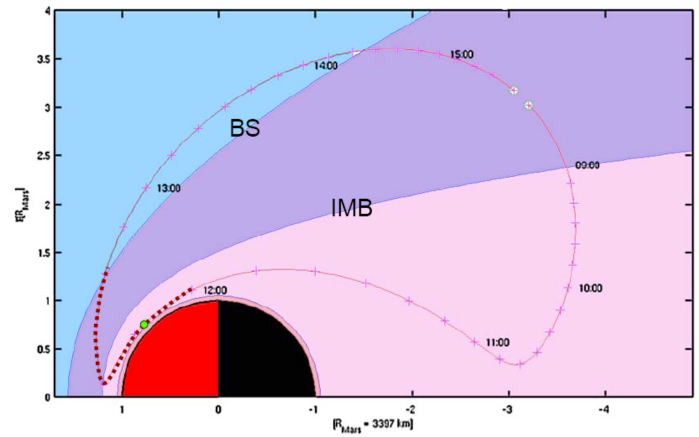


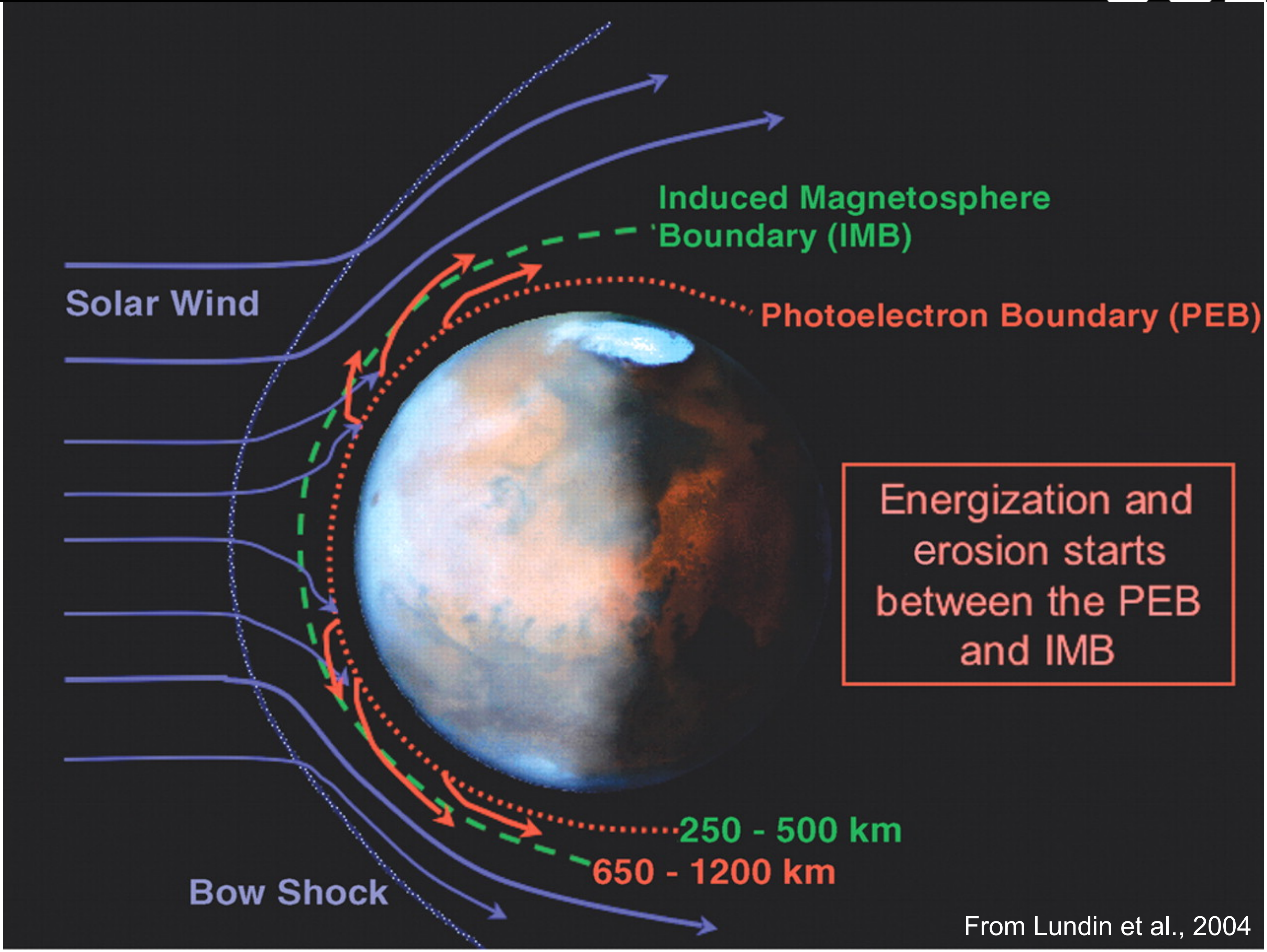
Figure 1. Cartoon of the global Martian solar wind interaction. Orange shading indicates density of planetary neutrals. Blue indicates relative density of solar wind ions in different plasma regions (labeled in black), separated by different plasma boundaries (labeled in magenta). Boundary names in this figure are those specific to MGS literature.

Schematic of solar wind-Mars interaction from Brain et al. 2007

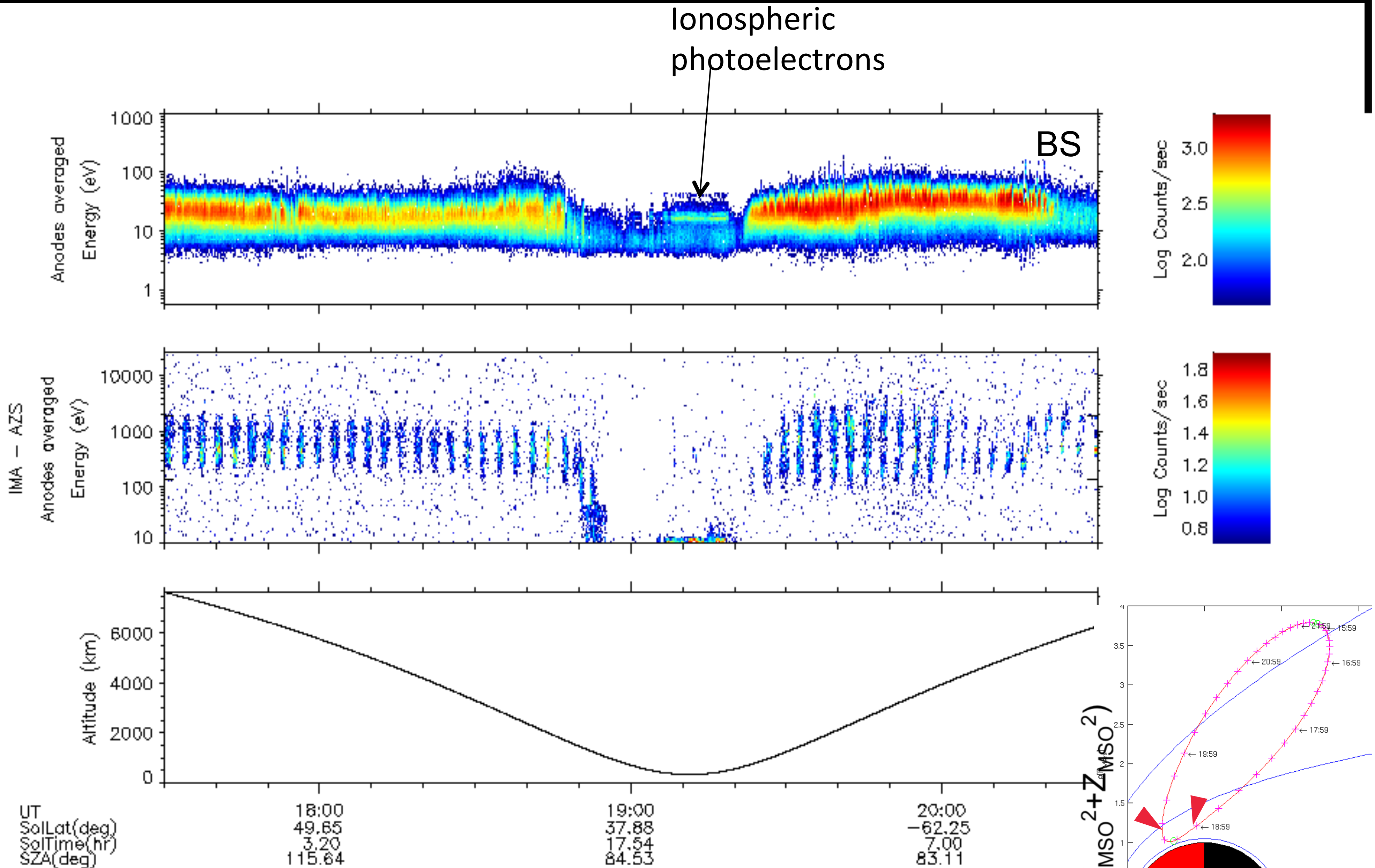




Lundin et al, Science, 2004



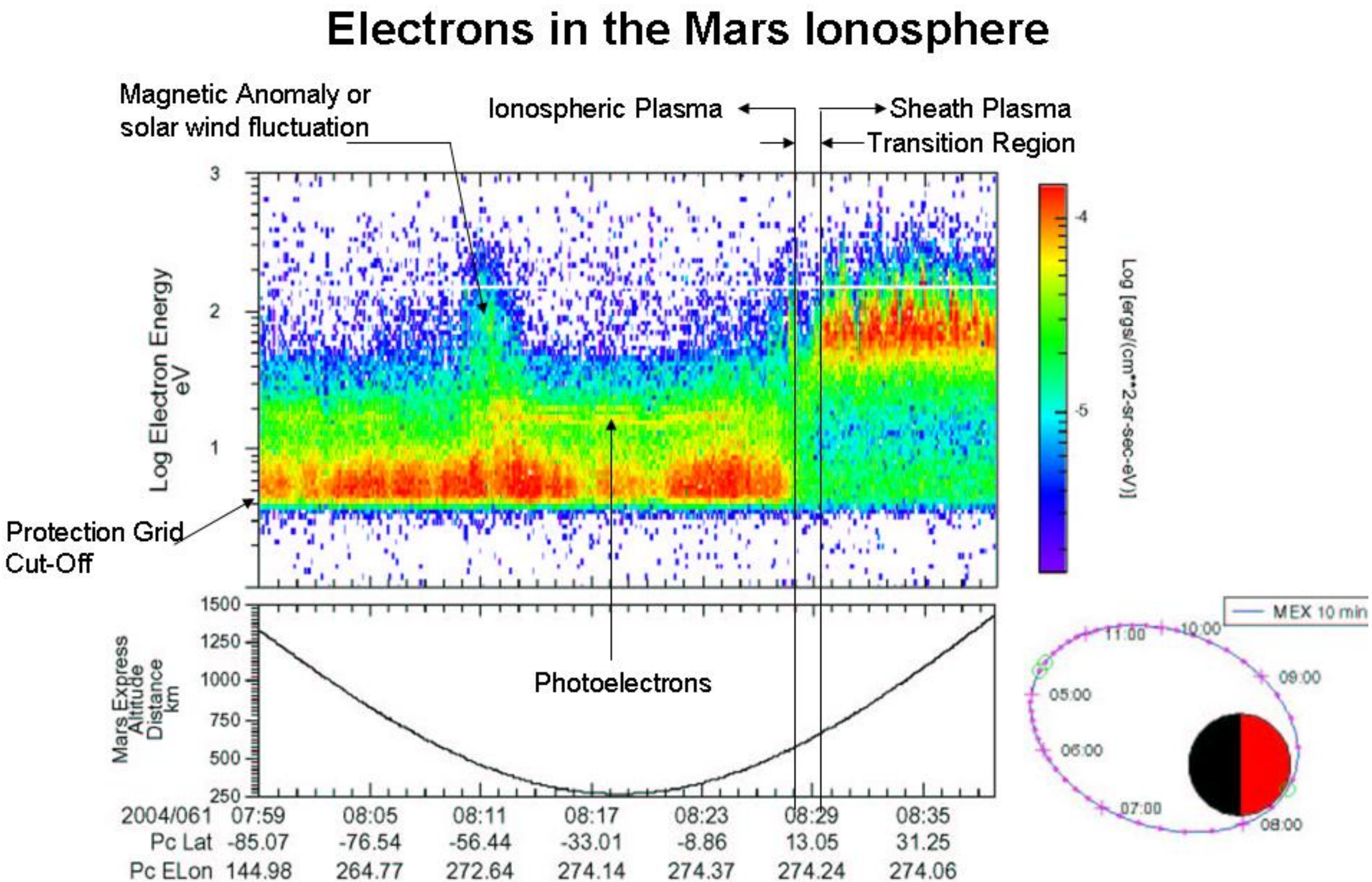
From Lundin et al., 2004



Mars Express ASPERA-3 example, 27 August 2009

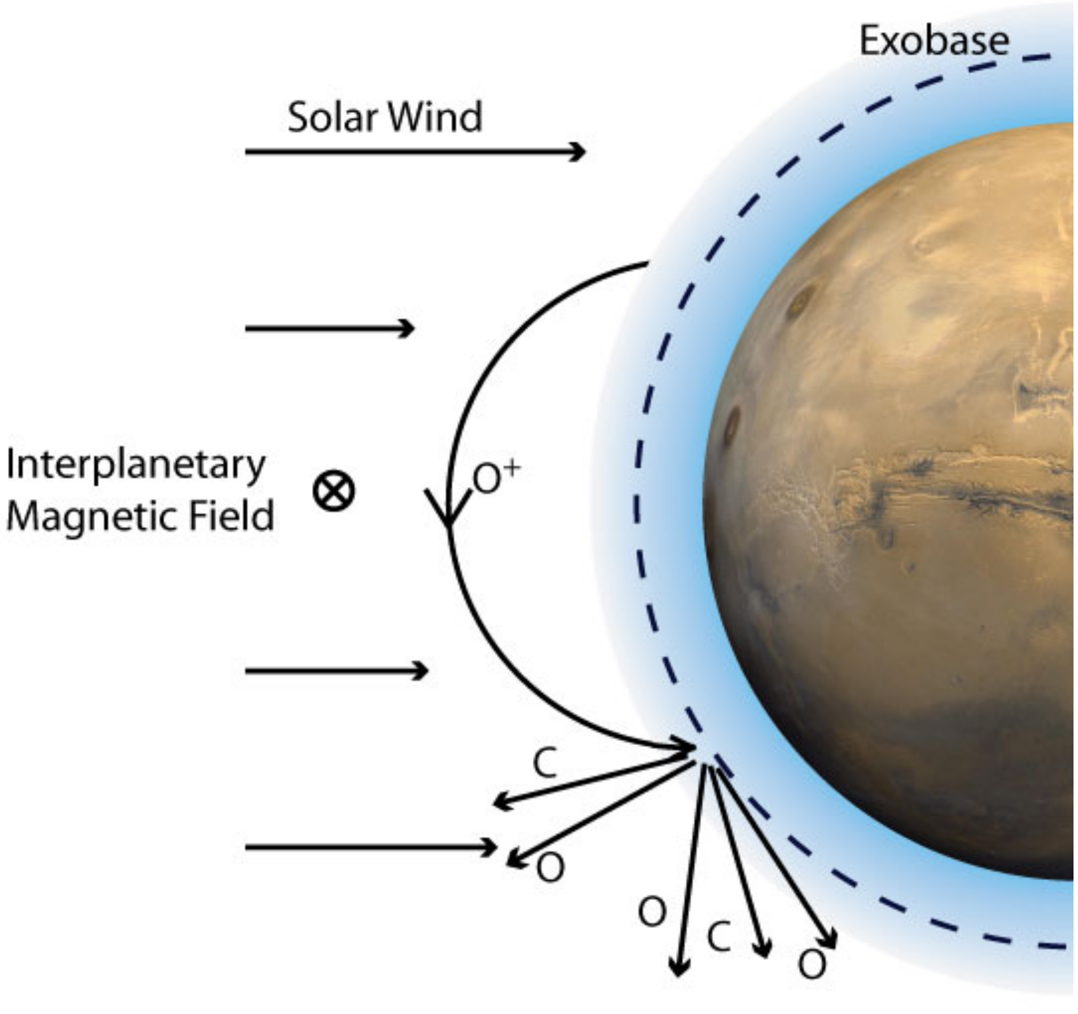
Coates et al., (PSS, 2011)

Mars interaction



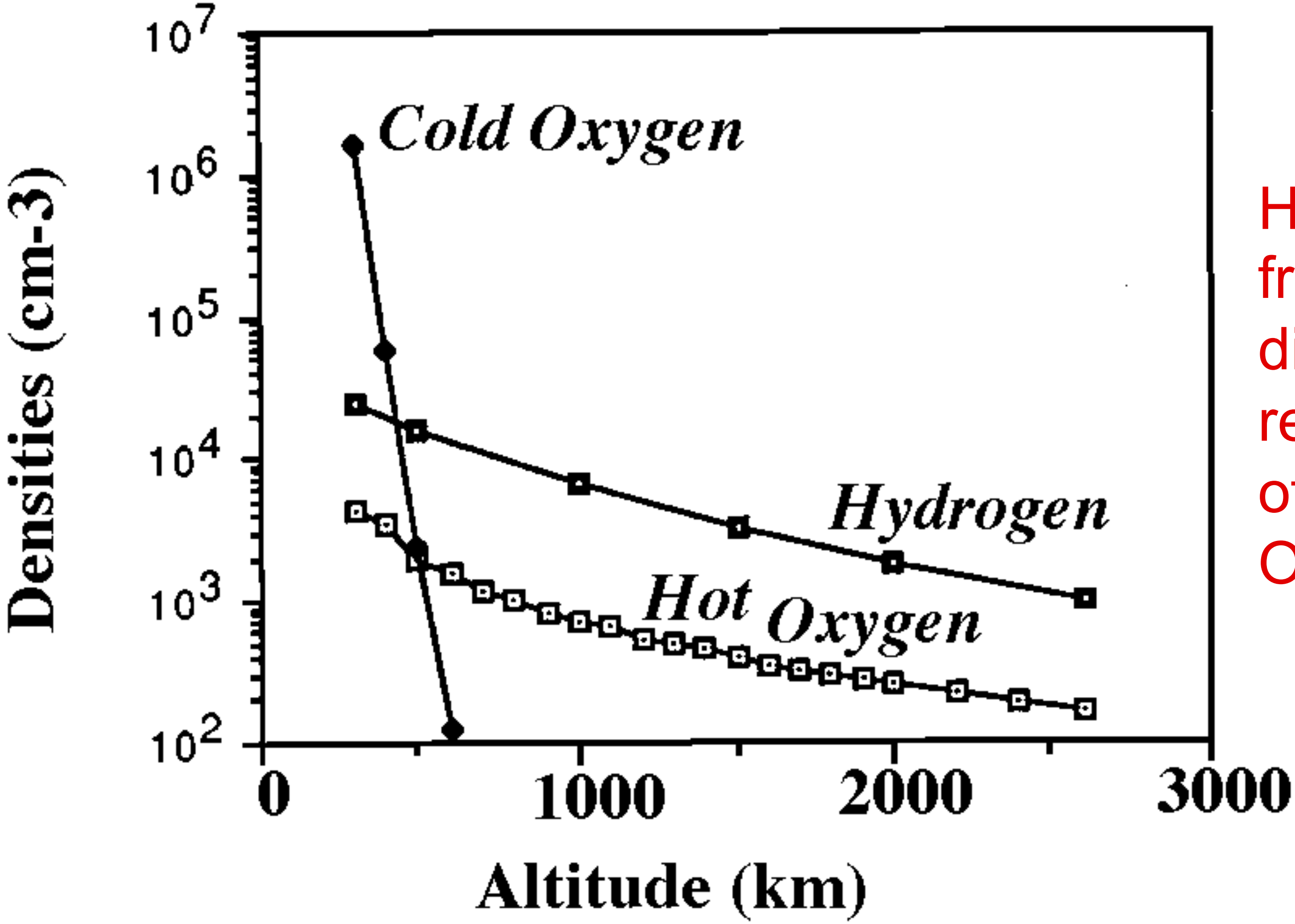
Mars exosphere

• Part of the atmosphere with a very low density, where collisions can be neglected.
• Atmospheric escape region
• Lower limit: “Exobase”, in the altitude range 160-200 km.



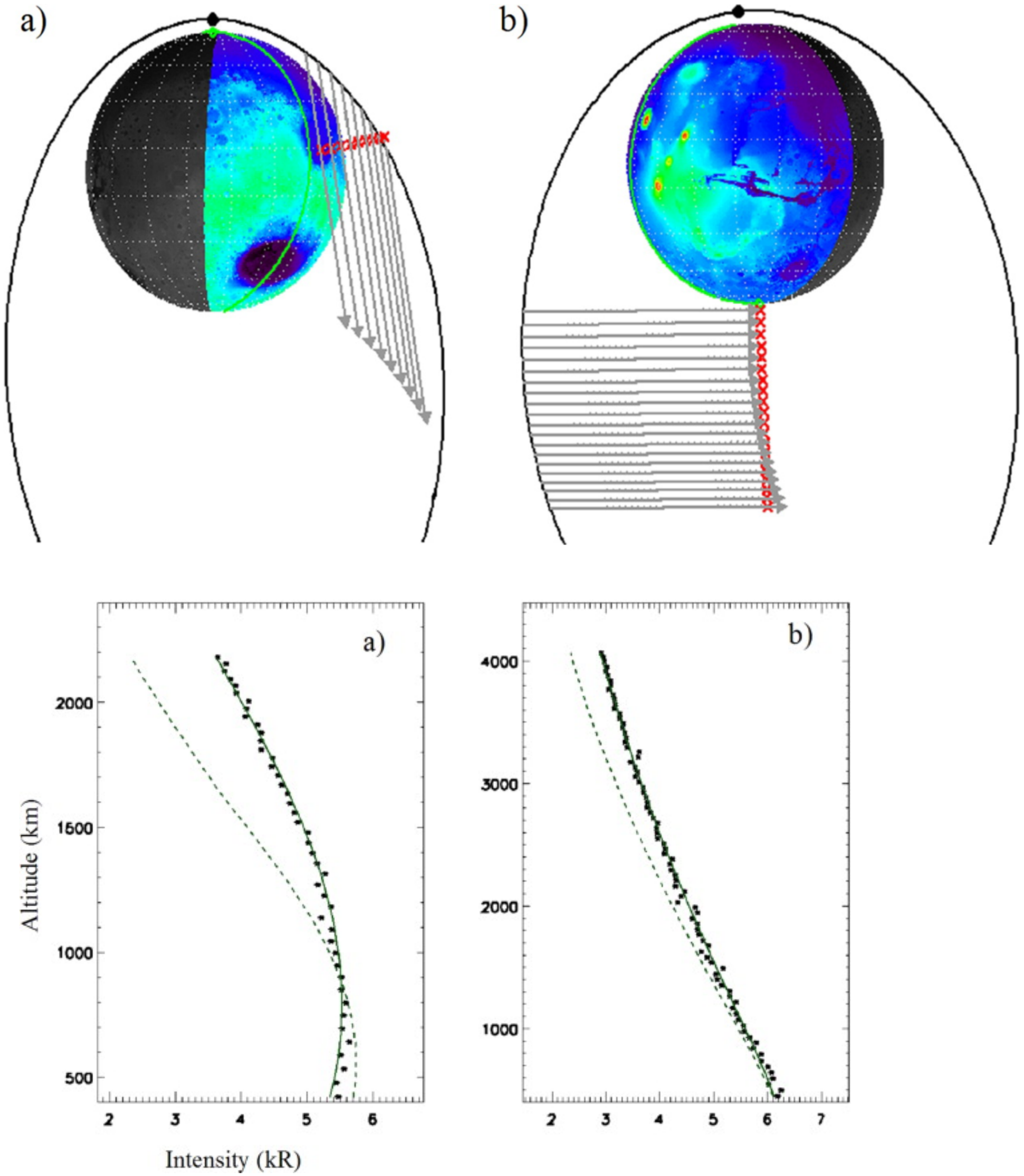
After Luhmann and Kozyra (1991)

A "cometary" interaction partially applies to Mars due to its extended hydrogen and oxygen exosphere.



Hot O from dissociative recombination of ionospheric O_2^+ ions

SPICAM measurements of the Hydrogen corona



Best fit obtained for the observation at low Solar Zenith Angle (SZA) (a) and high SZA (b) with two populations, the first is a “cold” population with exospheric temperature equal to 200 K and the second is a “hot” population assumed to be present only above the exobase (at 200 km). The single cold population intensity contribution is shown as dashed line. Adding some hydrogen from the hot population increases the intensity everywhere,

Chaufray et al. 2008

Solar Wind Interaction with Mars

- The solar wind interaction with Mars has characteristics of Venus-like, Earth-like, and comet-like interactions although it appears that the Venus-like is dominant.
- Evidence for plasma boundaries
  - Bow shock
  - Induced magnetosphere boundary
  - Photoelectron boundary

Mars bow shock

- Some mass loading effects due to upstream pickup but very low density
- Contrasts to cometary case where pickup occurs within shock
- Particle distributions used to infer magnetic field (Yamauchi et al., 2011)

Comet bow shock – pickup ions important

Produces low Mach number (1-2) shock (Coates et al., 1997)

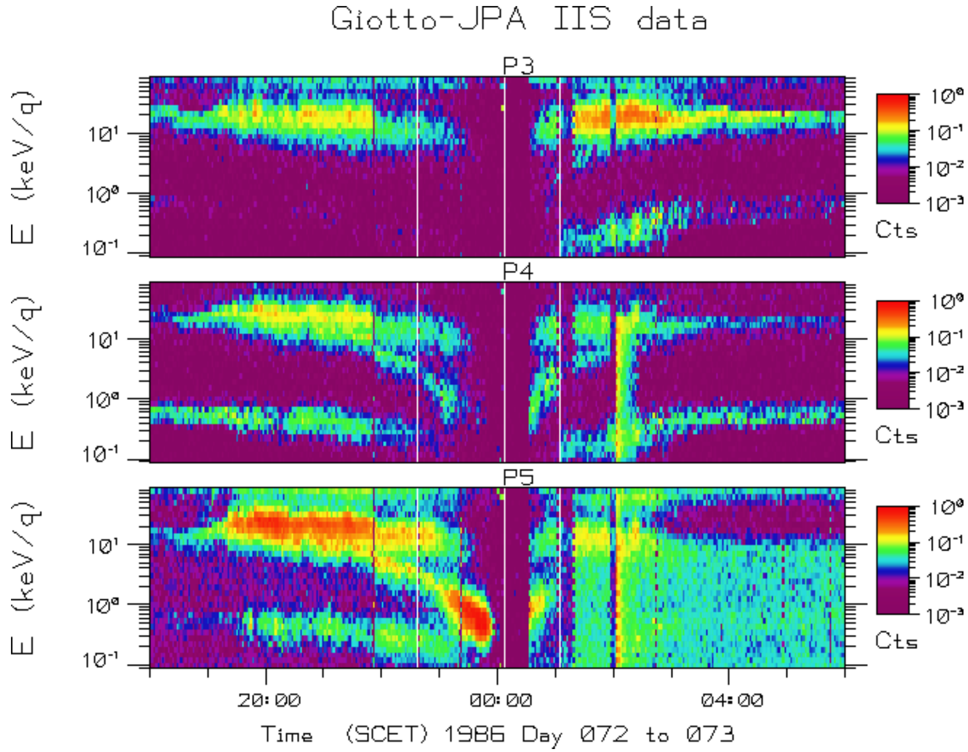
Data from Giotto at Halley (Johnstone et al, 1986)

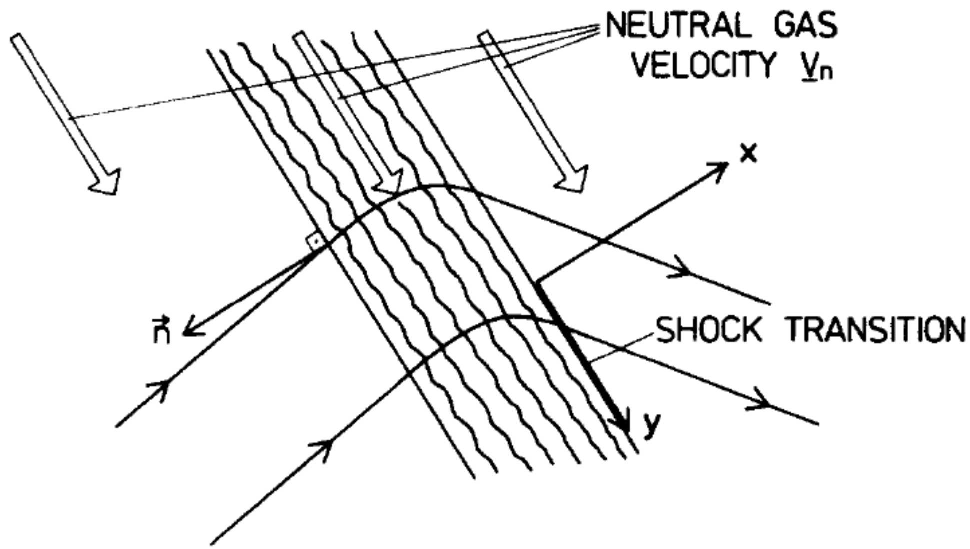
Bifurcation due to slowing of flow (Thomsen et al 1987)

Outbound Halley bow shock

Broad, quasi-∥ structure (120,000 km) – ionisation within structure important (Neubauer et al, 1990)

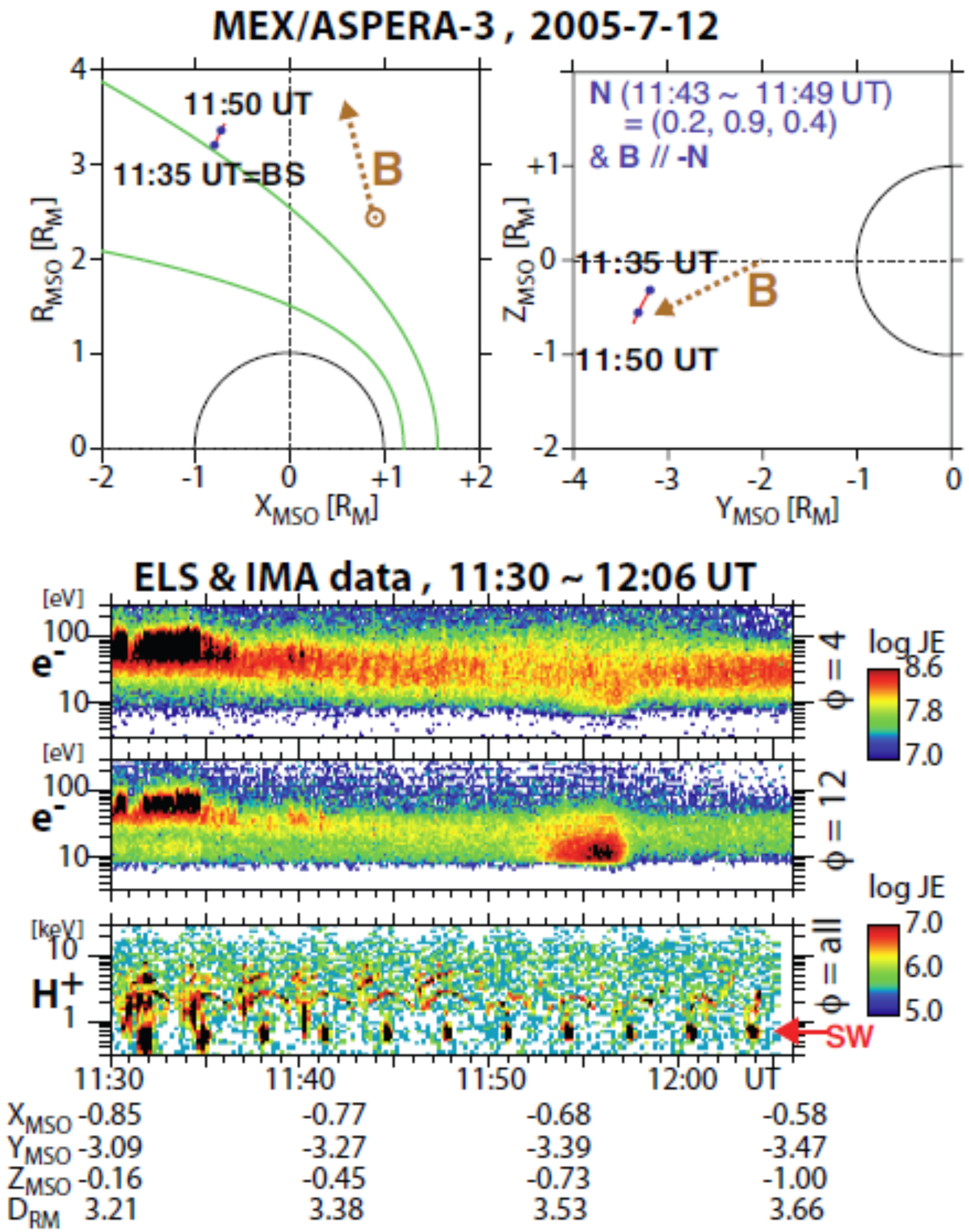
See summary by Coates, AIP proceedings, 2009





Recent Mars bow shock analysis

- Pickup of protons from Mars' exosphere upstream of shock
- Nested reflected ion populations in shock region
- Indicates multiple specular reflection at shock



Yamauchi et al., Ann Geo., 2011

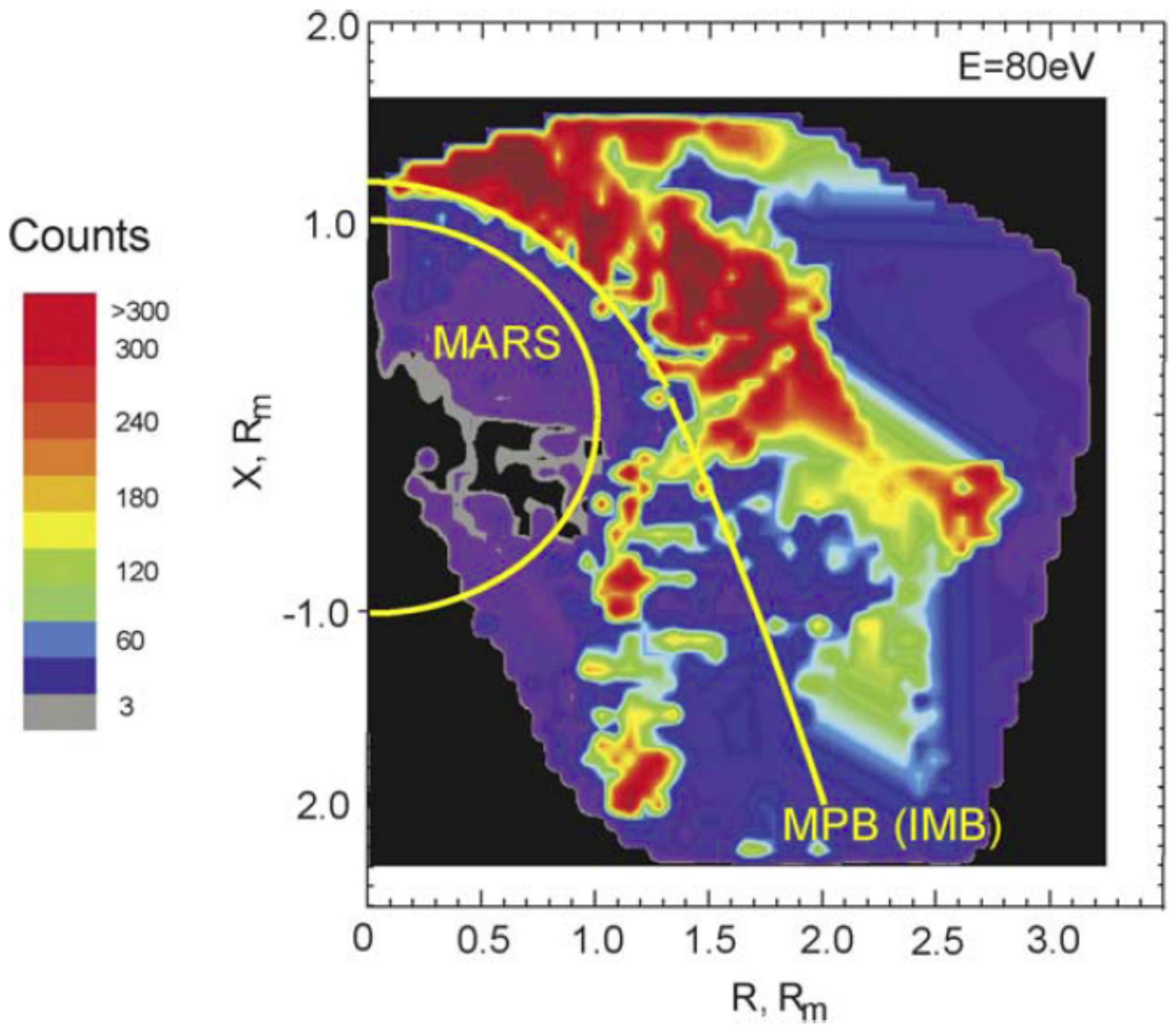


Fig. 3. Image of the electron fluxes at a fixed energy ($E_e = 80$ eV) near Mars cylindrical coordinates (~50 MEX orbits). MPB denotes the magnetic pile boundary found from the MGS observations.

Magnetic pileup boundary (MPB) or Induced Magnetosphere Boundary (IMB) – intermediate between bow shock and ionopause

Dubinin et al 2006

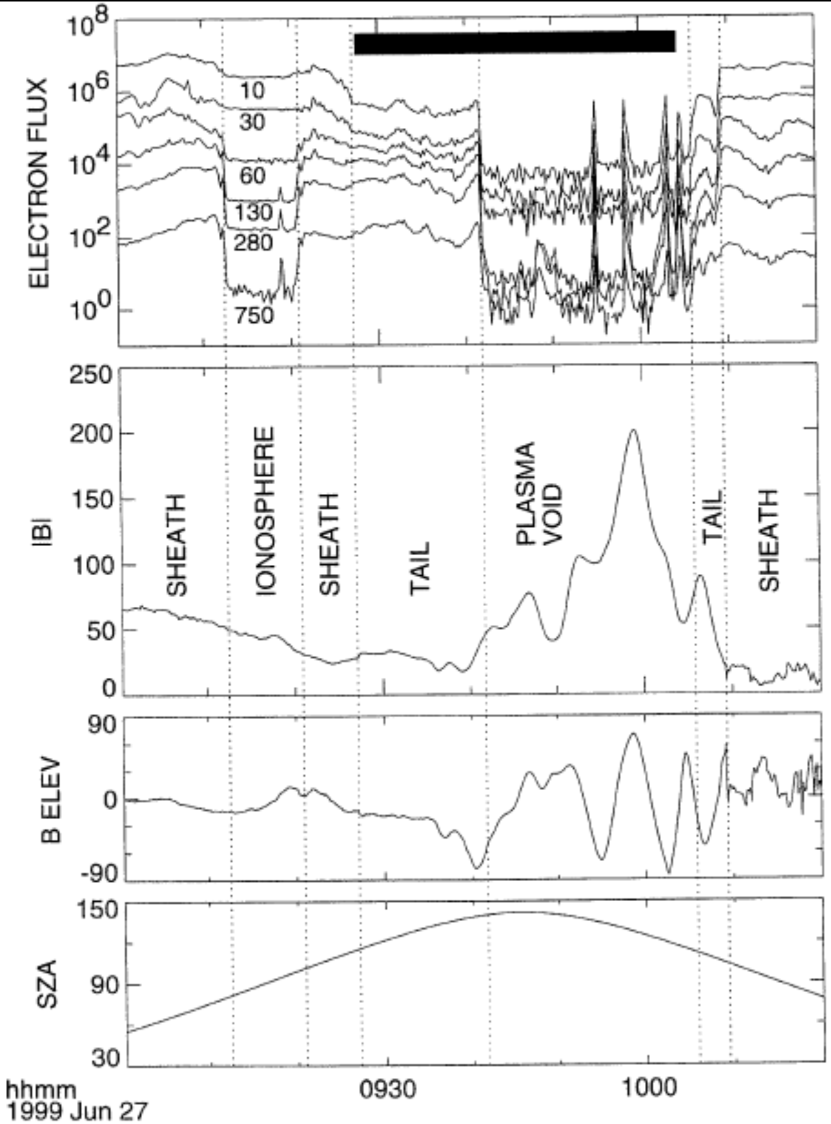


Figure 6. An expanded view of one of the plasma voids shown in Figure 5, divided into seven distinct plasma regions (vertical dashed lines) on the basis of electron energy spectra (see Figure 7). Electron flux spikes within the plasma void tend to occur when the magnetic field has a large radial component.

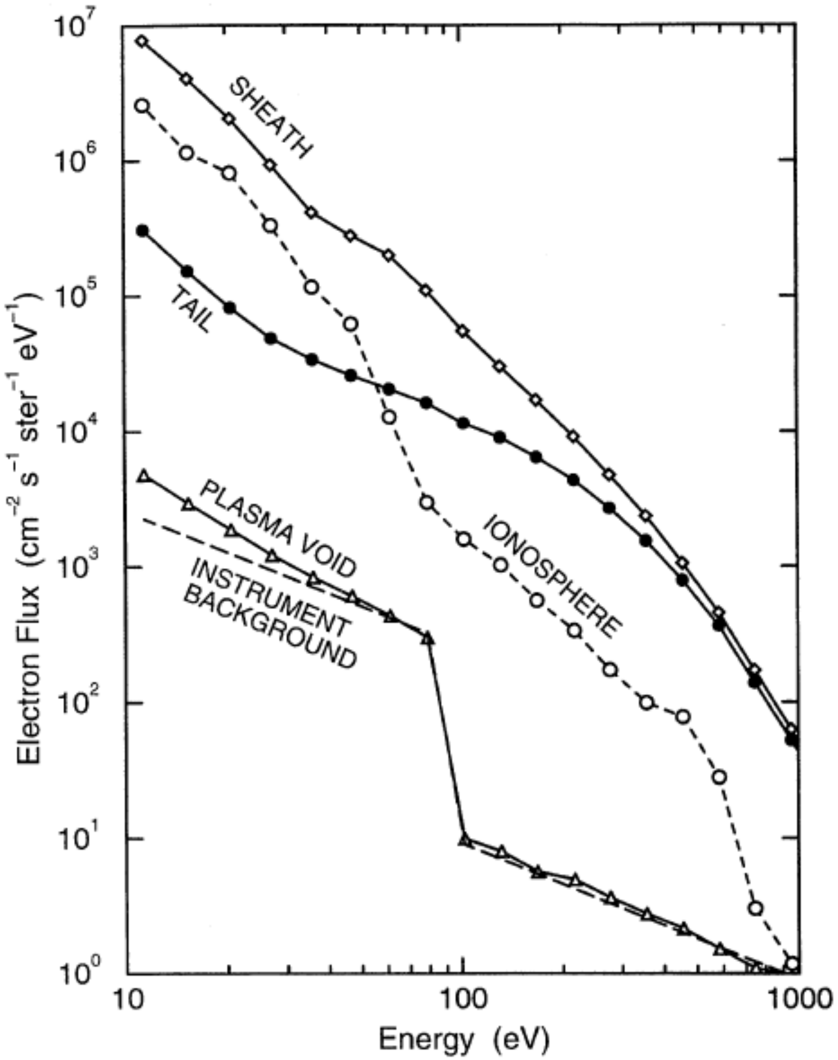


Figure 7. Electron energy spectra that define the different plasma regions identified in Figure 6.

MGS data showing inner region and 'plasma voids' Mitchell et al., 2001

Evidence for reconnection in Martian tail

MGS observations – 4 pieces of evidence:

1. Hall magnetic field structure – bipolar variation in Bm
2. Current sheet bifurcation
3. Enhanced wave activity
4. Secondary magnetic island

Eastwood et al., 2008

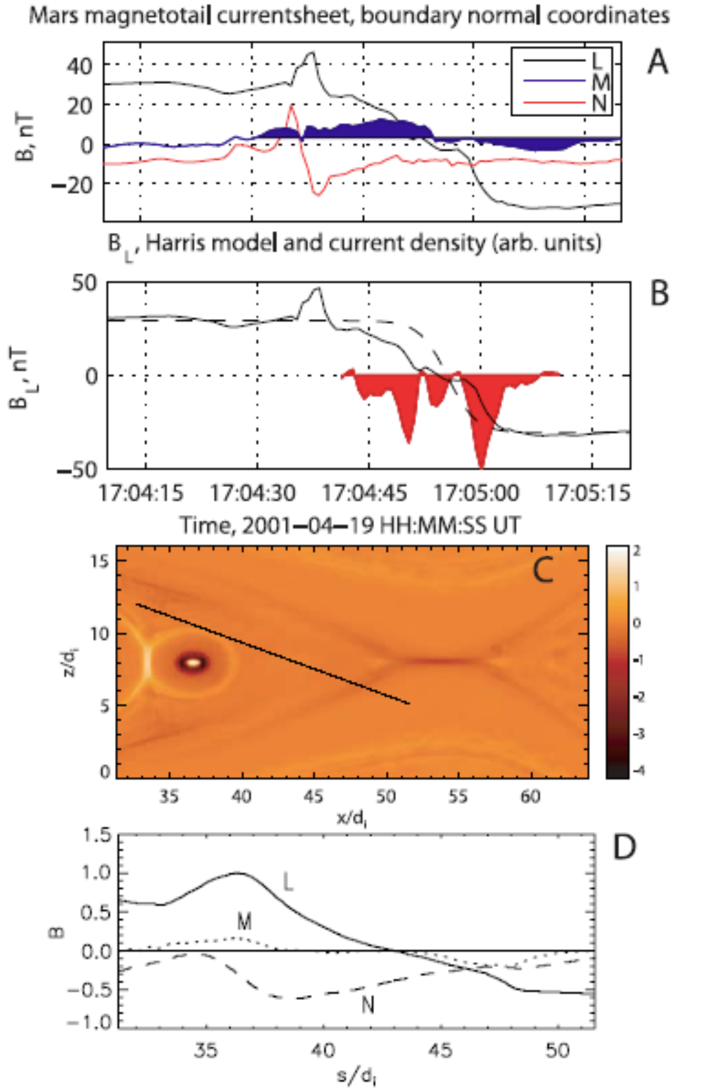
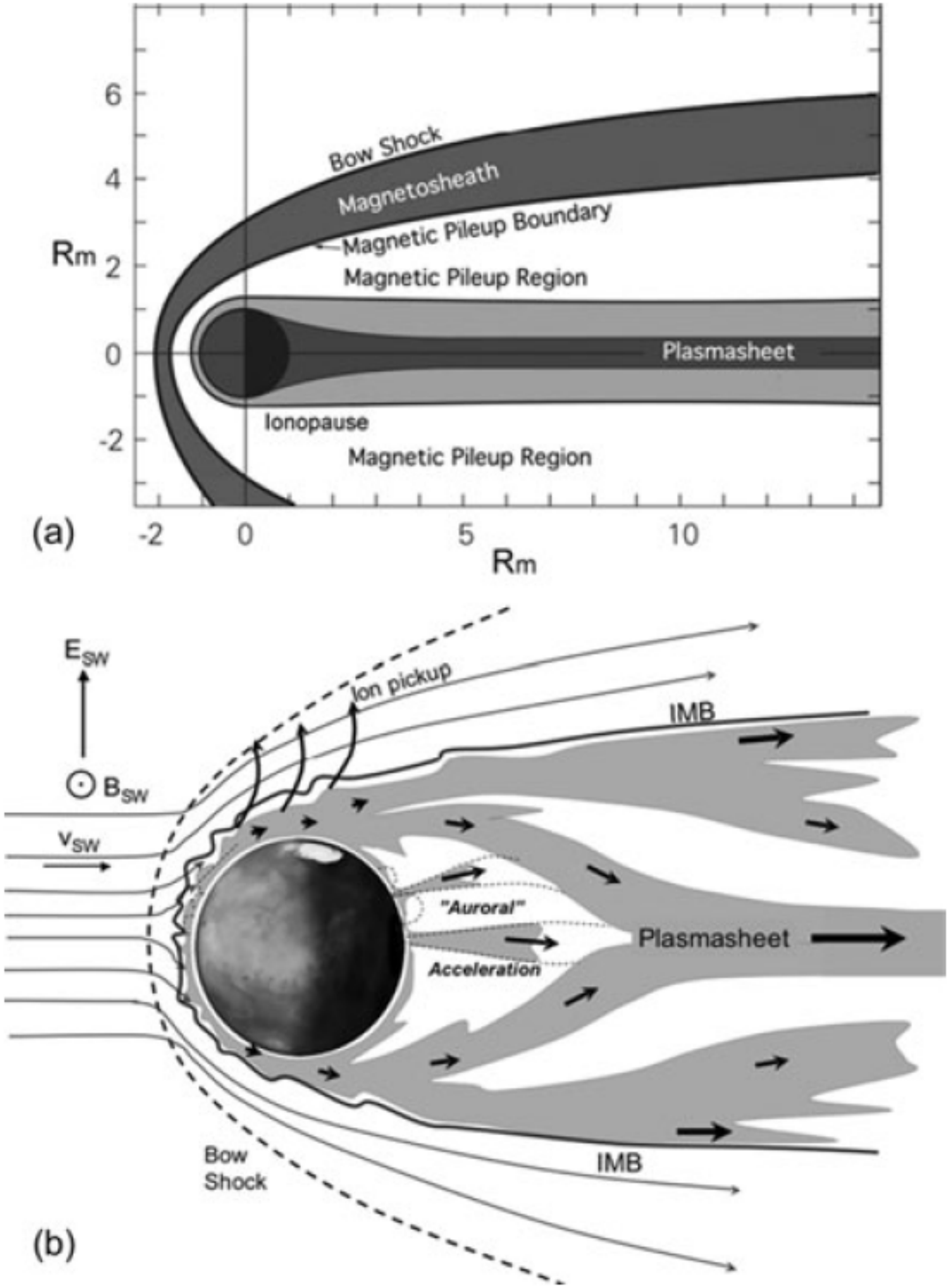
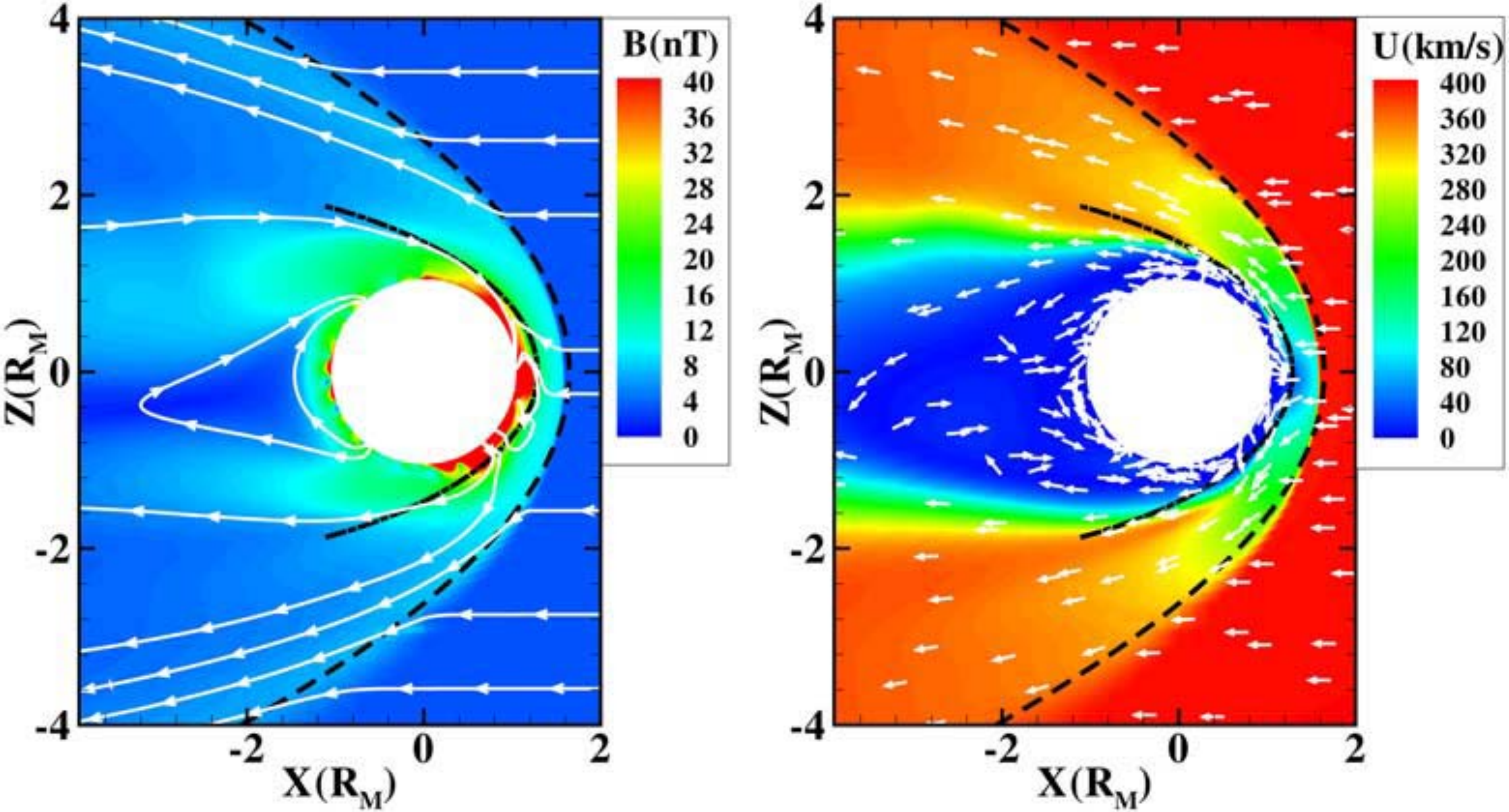


Figure 3. (a) Magnetotail crossing in boundary normal coordinates. (b) B_L (black), a Harris current sheet model fit (dashed black) and the current density j_M (red). (c) Out of plane current density from a Particle-In-Cell simulation of magnetic reconnection. (d) Variation in the magnetic field along the diagonal cut shown in Figure 3c. This cut corresponds to the trajectory of the spacecraft, as inferred from the data and shown in Figure 4.

Fig. 1 Solar wind interaction with Mars. (**a**) Structure of the Martian plasma environment based on primarily Phobos-2 and MGS results (Nagy et al. 2004). (**b**) Diagram illustrating the energization and average flow of ionospheric plasma escape based on recent ASPERA3 measurements from Mars Express



Lundin, SSR 2011



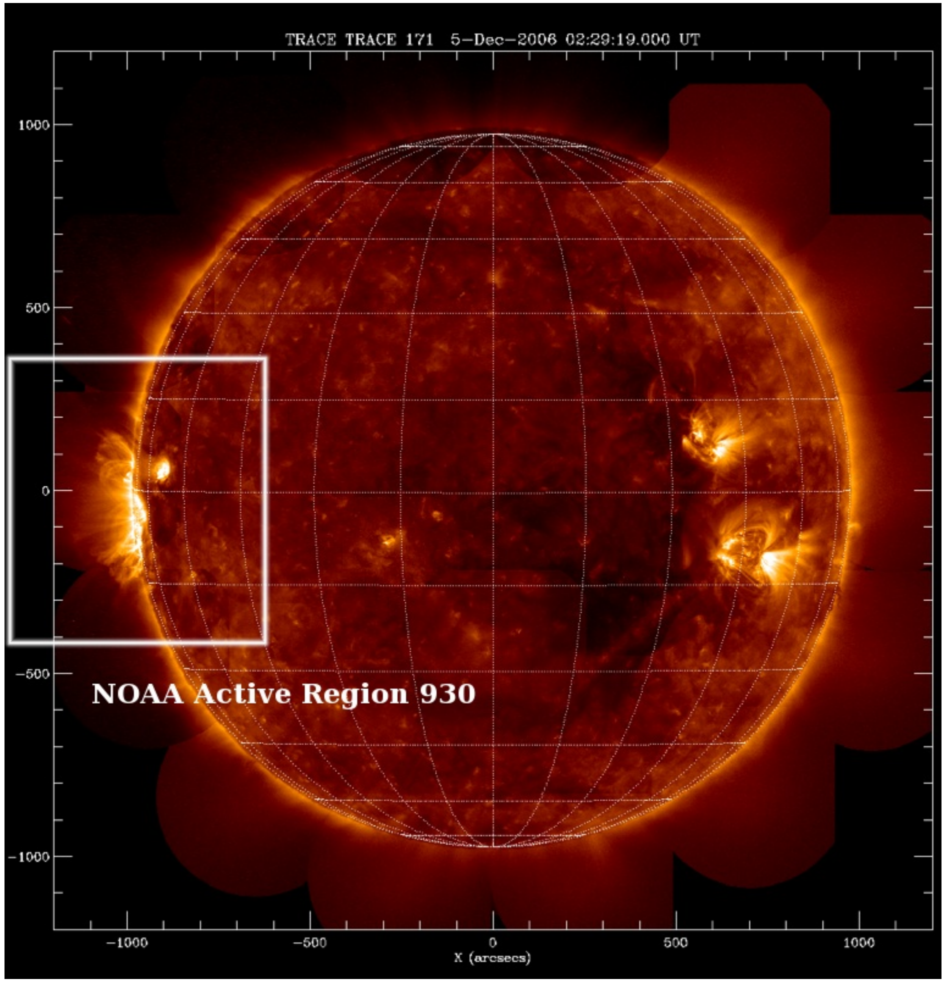
Multi-species Global MHD Model: Flow and Magnetic Field Results. From Ma et al. (2004)

Mars space weather effects

- Upstream plasma supersonic, SuperAlfvenic so bow shock (Phobos, MGS, MEX)
- Scale of interaction not as sensitive as Venus to solar wind conditions
- Induced magnetosphere: field draping (Phobos, MGS)
- Photoelectron production
- Auroral emissions, accelerated electrons on night side (Bertaux et al, Lundin et al) – associated with acceleration over crustal fields
- Plasma escape
  - Preliminary measurements (Barabash et al, Science, 2007) show lower escape flux than expected – implications for where early Mars water went
  - Measurement did not include lowest energy ions
  - Escape rate sensitive to solar wind conditions
- Crustal fields may affect low energy plasma escape

SOLAR FLARES ON DEC 5 - 14, 2006

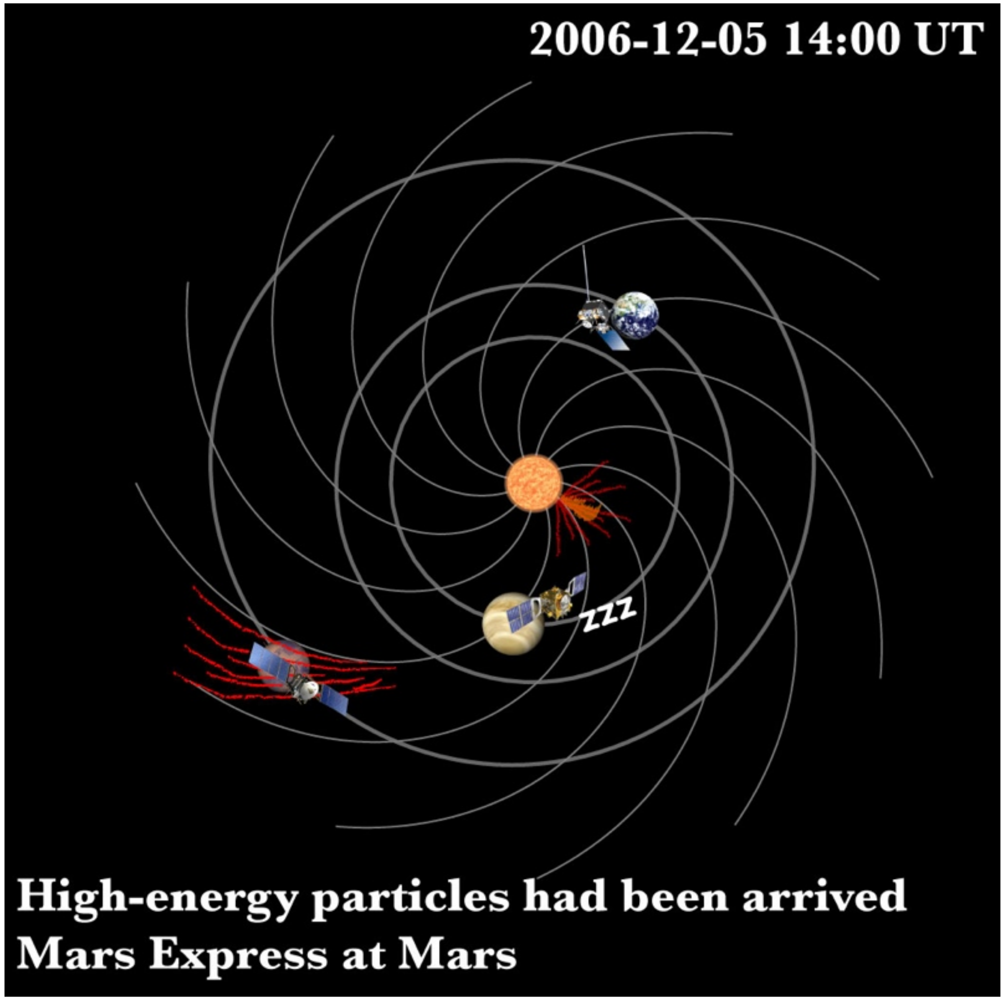
- The active region NOAA 0930 made a series of X-class flares in December 2006
  - X9.0 (December 5, 10:34UT) @ (E79, S07)
  - X6.5 (December 6, 18:42 UT)
  - X3.4 (December 13, 02:24 UT)
  - X1.5 (December 14, 22:10 UT)



TRACE data
2006-12-05 02:29 UT

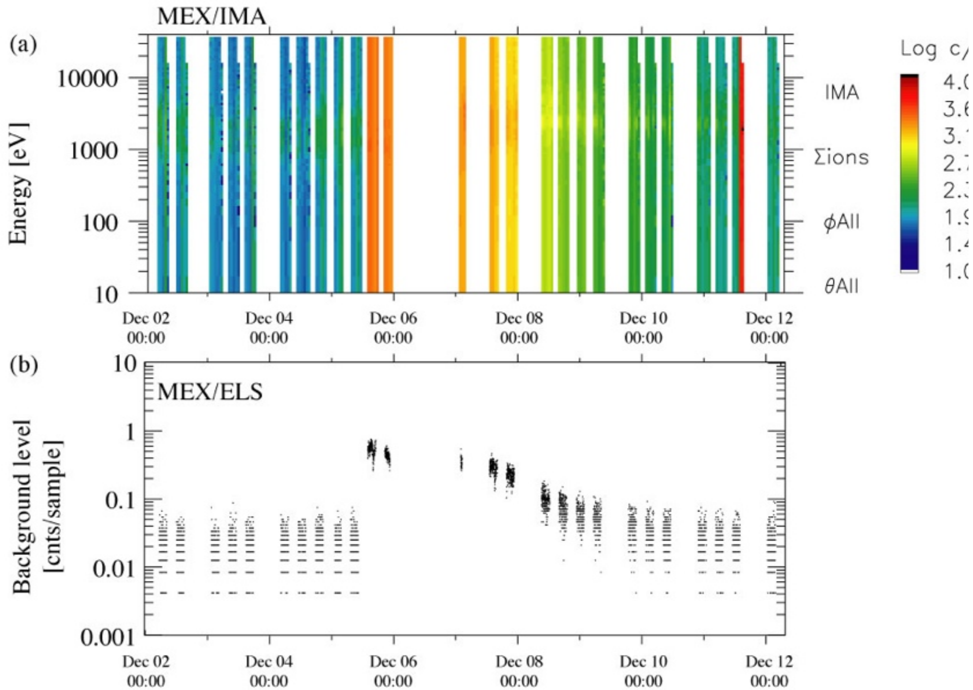
Futaana et al., PSS 2008

SEPs at Mars

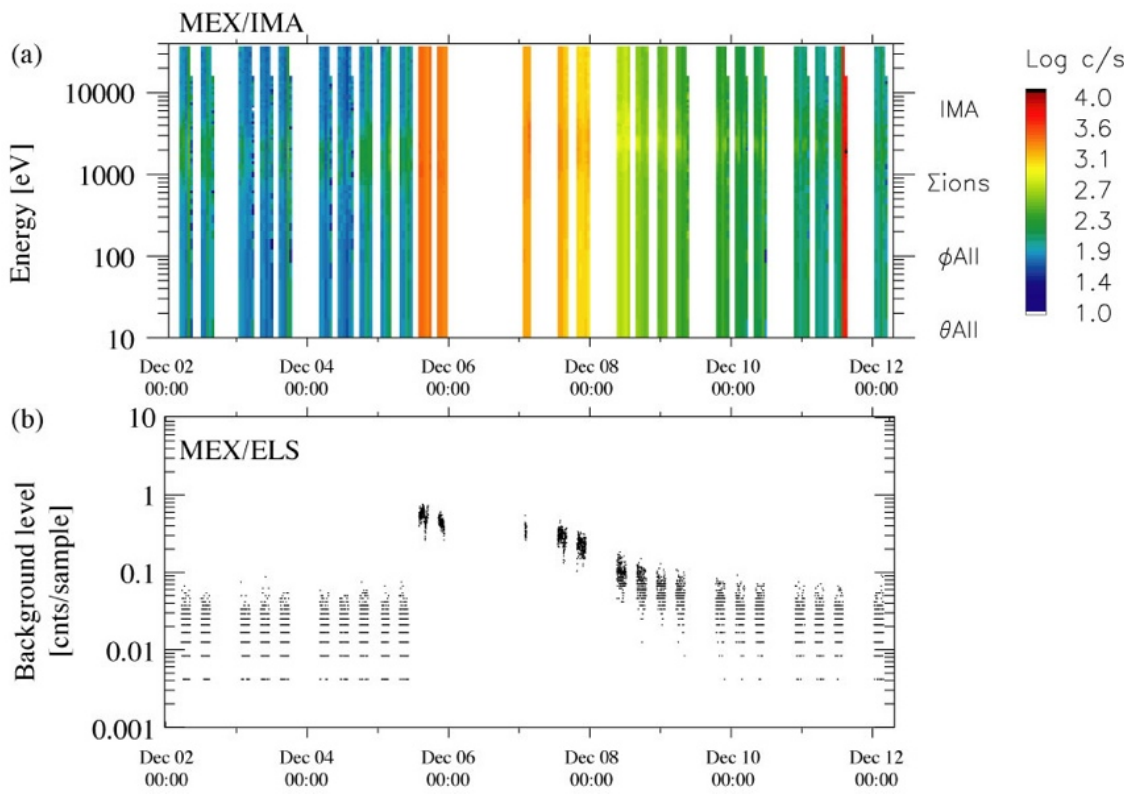


Futaana et al., PSS 2008

- SEPs (=increases of IMA/ELS background level) had been arrived before 14UT on 5 December
  - SEPs flying time was less than 3.5 hrs.



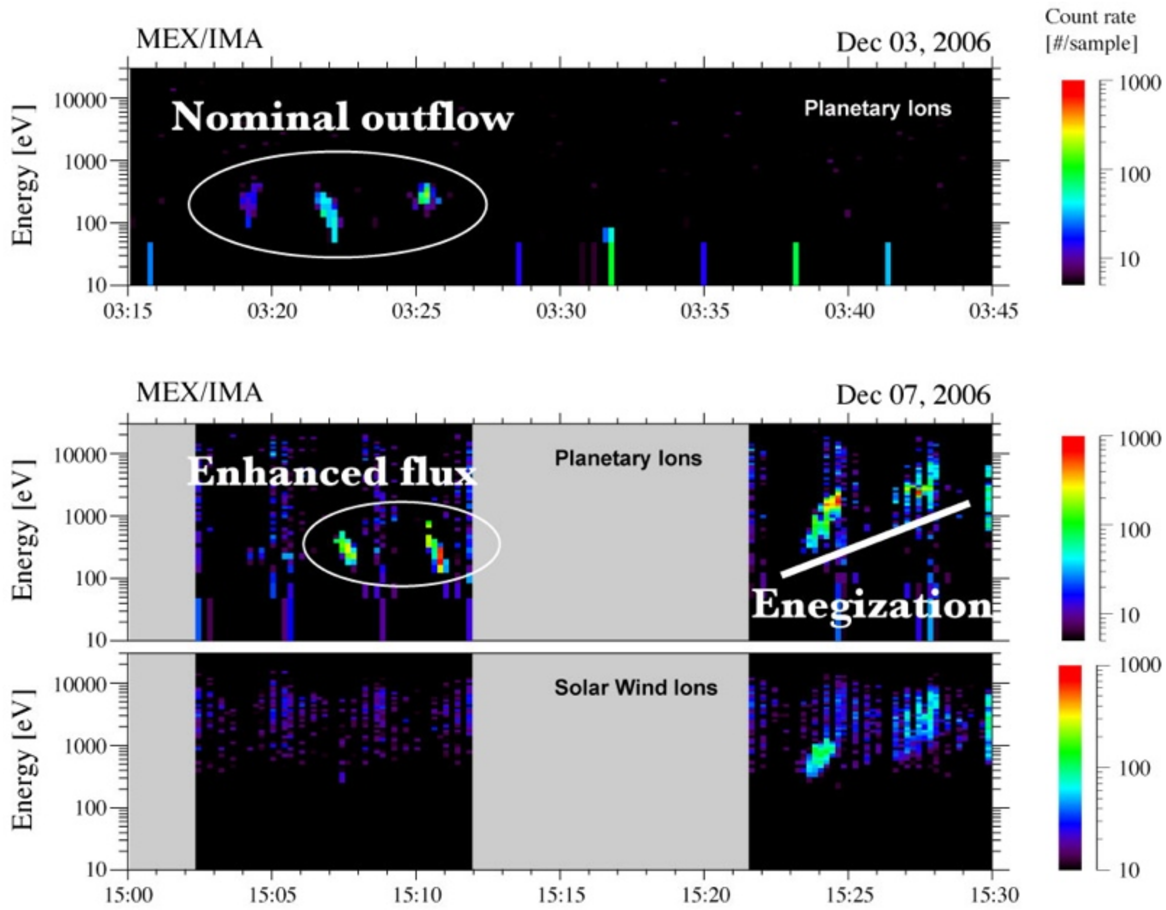
CME at Mars



- MEX/IMA the solar wind measurements are affected by SEP during the period until December 9, 2006. No clear identification of CME.

Futaana et al., PSS 2008

Influence on Mars ion outflow

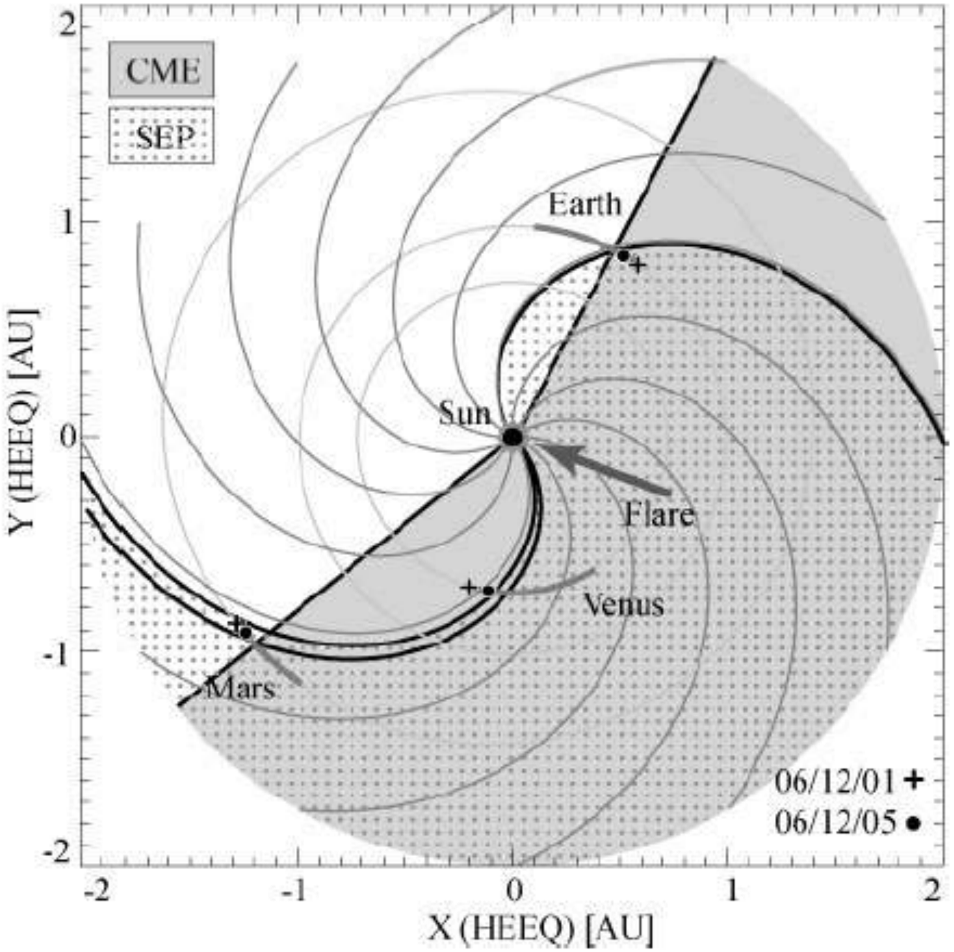


- During the SEP event, MEX/ASPERA-3 recorded energization (up to several keV) and enhancement of ion outflow flux (~5-10 times).

Futaana et al., PSS 2008

Summary (1)

- The active region NOAA 0930 made series of geo-effective X-class flares in December 2006.
- VEX and MEX at Venus and Mars detected associated SEPs by measuring increases of the ASPERA sensors background levels.
- VEX recorded the CME signatures resembling those recorded at the Earth
- The SEPs and CMEs associated with the active region 0930 disturbed a large part of the heliosphere (±90° from the flare location)



Futaana et al., PSS 2008

X-rays from Mars

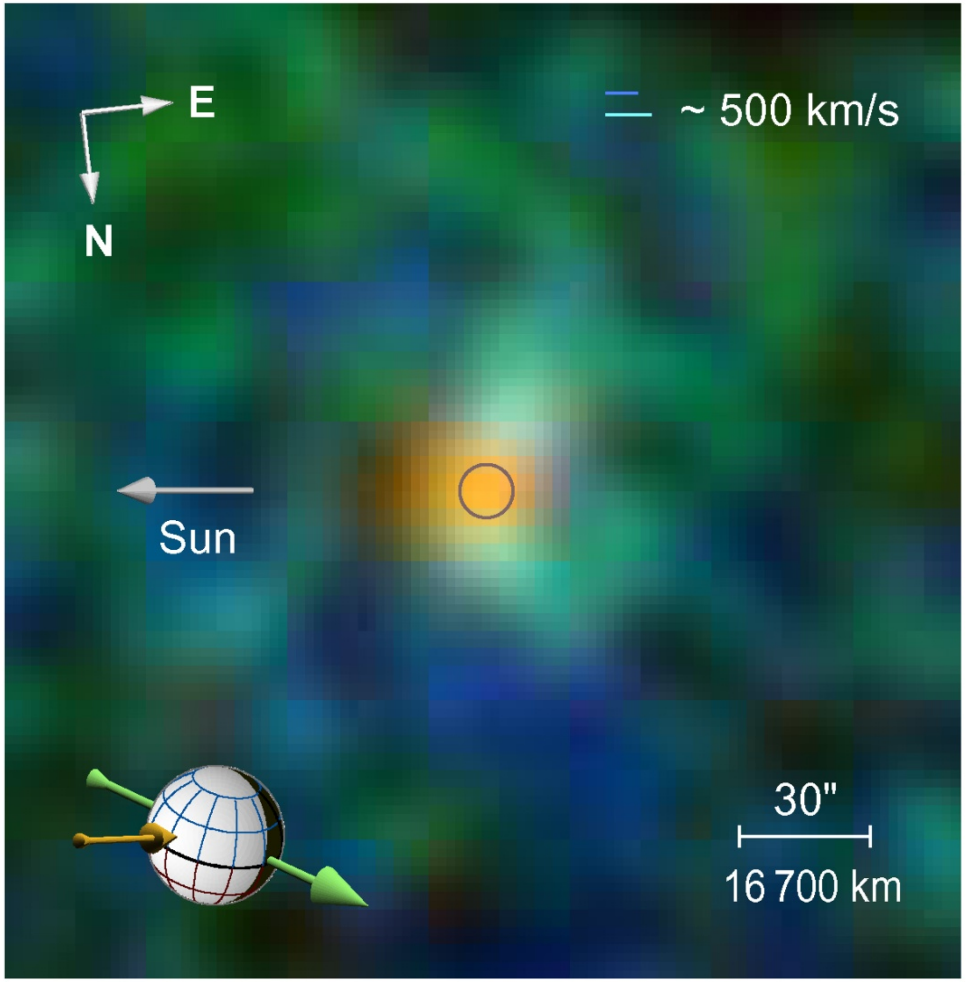


Fig. 19 Superposition of the XMM–Newton / RGS images in Fig. 18, each centered on the wavelength/energy of an individual emission line, with ionized oxygen coded in blue, ionized carbon coded in green, and fluorescence coded in yellow and red. The projected direction of the Sun is towards the left (horizontal arrow). The circle indicates the position and size of Mars; further details about the observing geometry are provided by the sphere at lower left: the grid shows areographic coordinates, with blue lines for the southern hemisphere (top) and red lines for the northern hemisphere (bottom). The bright part of the sphere is the sunlit side of Mars. A green arrow indicates its direction of motion, as seen from a stationary point at the position of the Earth. The yellow arrow illustrates the velocity of solar wind particles, emitted radially from the Sun with 400 km s^{-1} with respect to Mars (from Dennerl et al. (2006a)).

X-ray emission discovered from Mars.
Most recently, solar wind charge exchange emission from the Martian Exosphere (blue).

Dennerl et al. (2006) XMM-Newton observations.

e.g., $O^{7+} + H \dashrightarrow O^{6+*} + H^{+}$

Electron measurements for future missions – expect the unexpected!

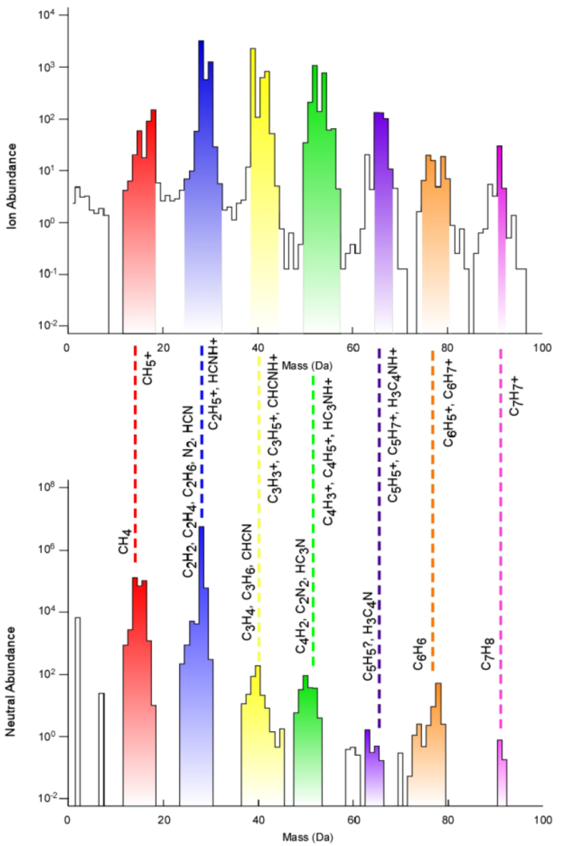
As we found in Saturn's system…

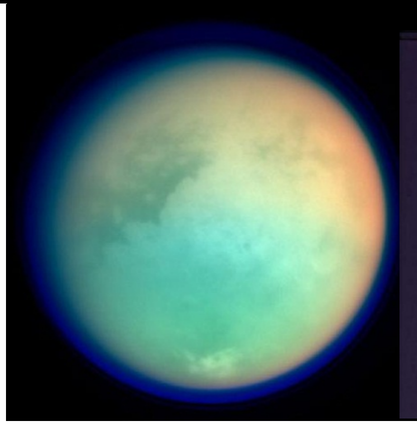
Titan's atmosphere: a rich chemical environment revealed by Cassini

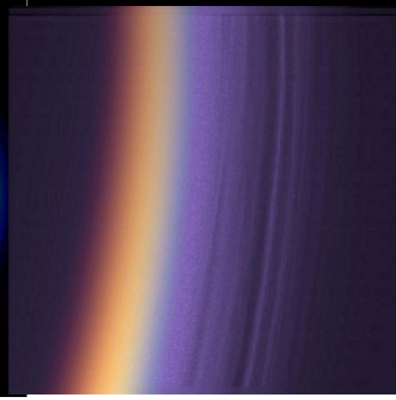
Negative ions:

- Seen in ram direction
- Heaviest (up to 13,800 amu/q) at lowest altitudes

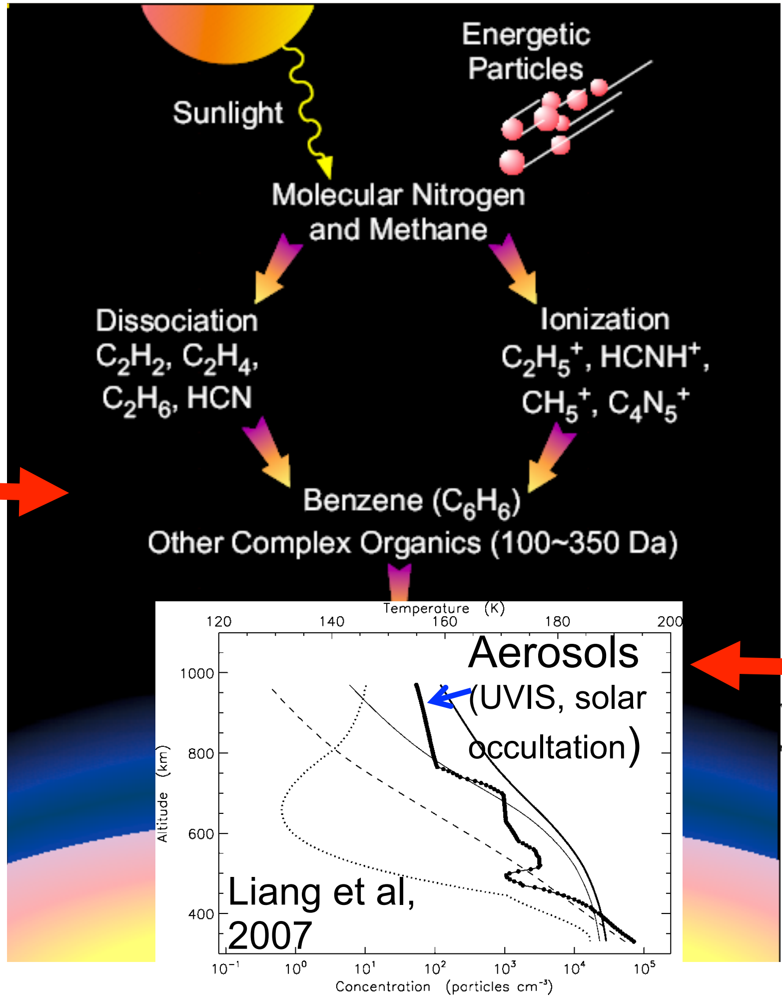
Unexpected heavy **negative ions**: Coates et al, GRL 2007a, PSS 2009, Coates PhTrRSA 2009, Coates et al Farad. Disc. 2010. Sittler et al PSS 2009, Michael et al PSS 2011

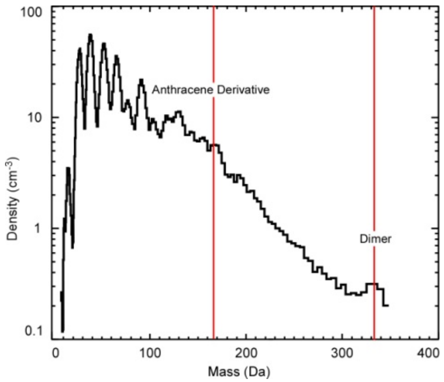


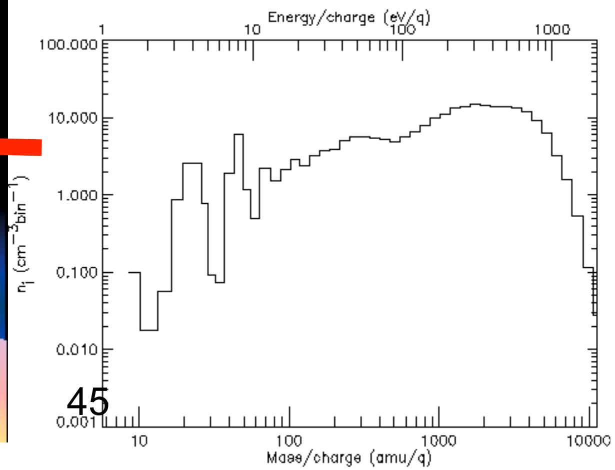


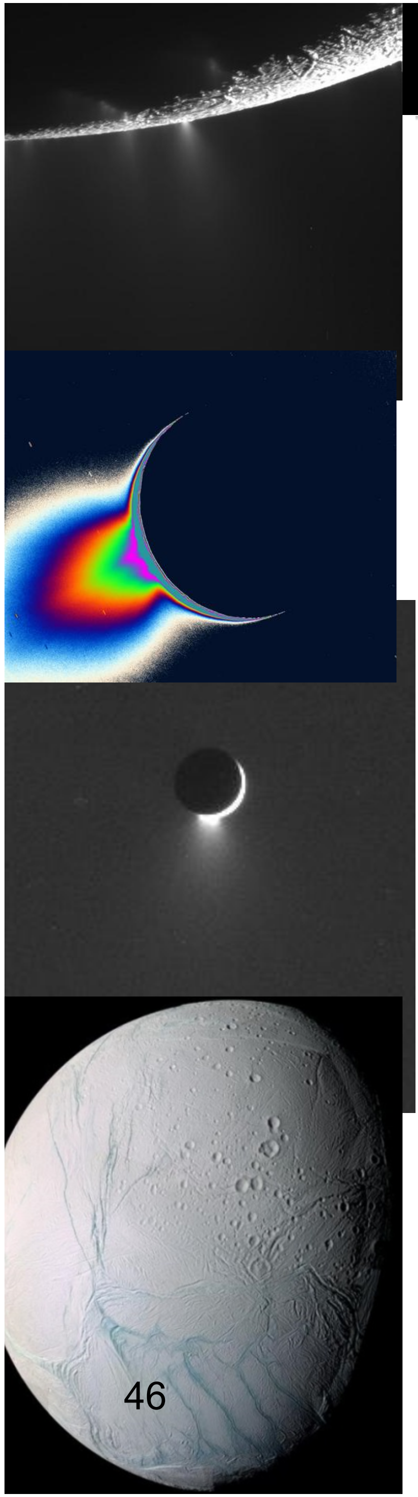


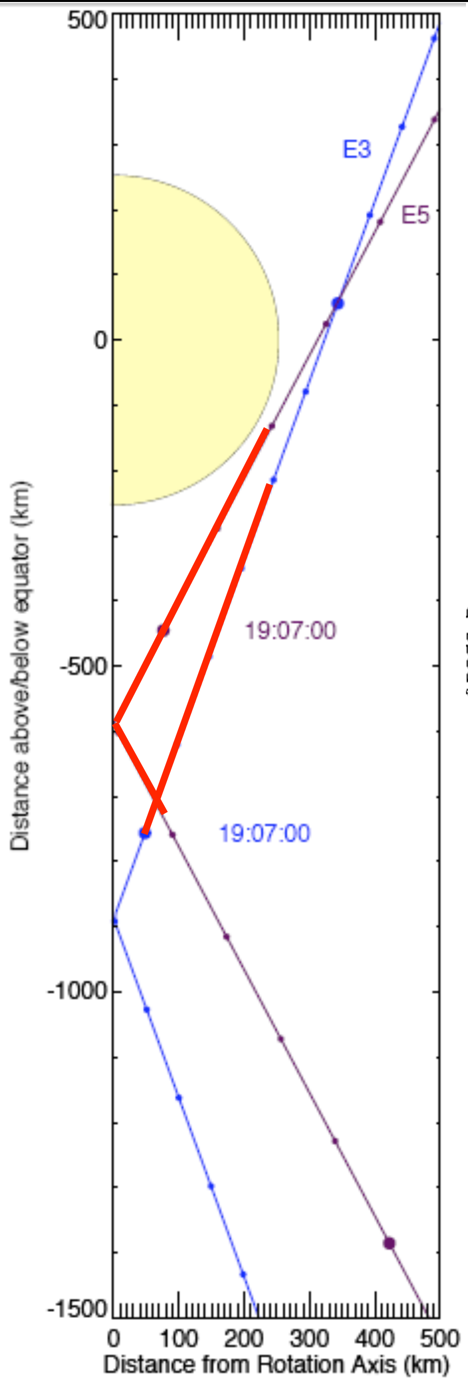
Heavy neutrals and positive ions: Waite et al, Science 2007, Crary et al. PSS 2009)



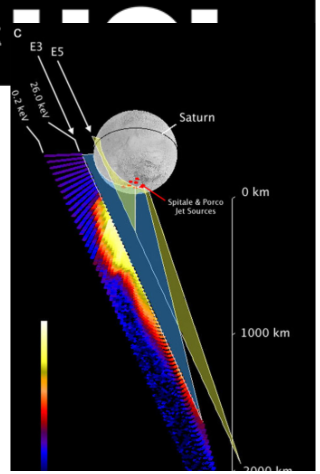






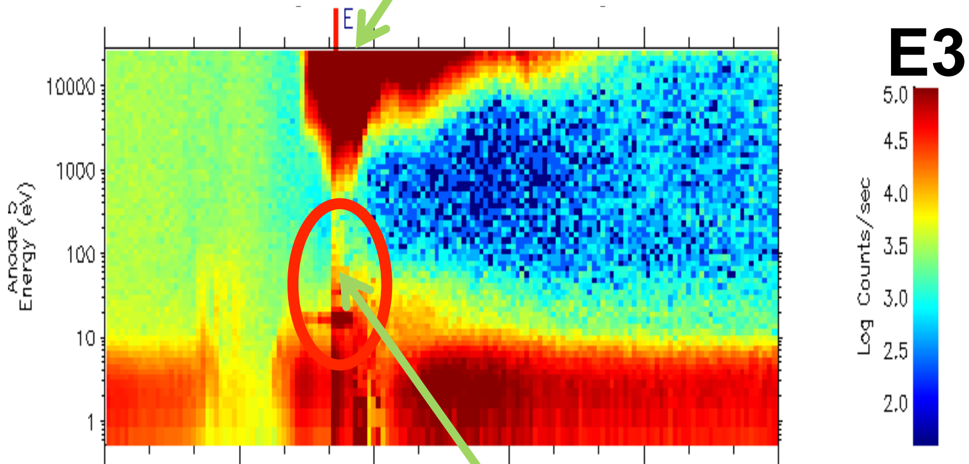


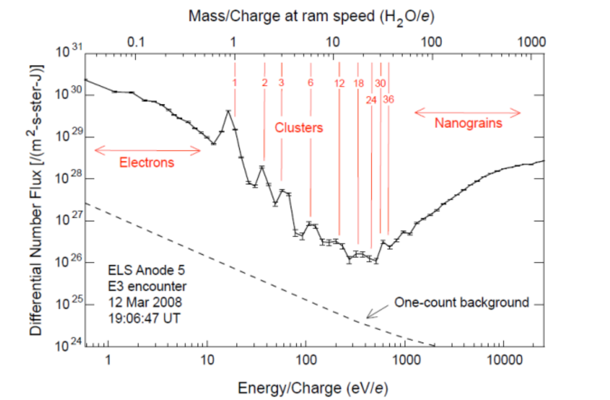
Unexpected discoveries from Cassini at Enceladus



Charged nanograins

Jones et al., GRL, 2009





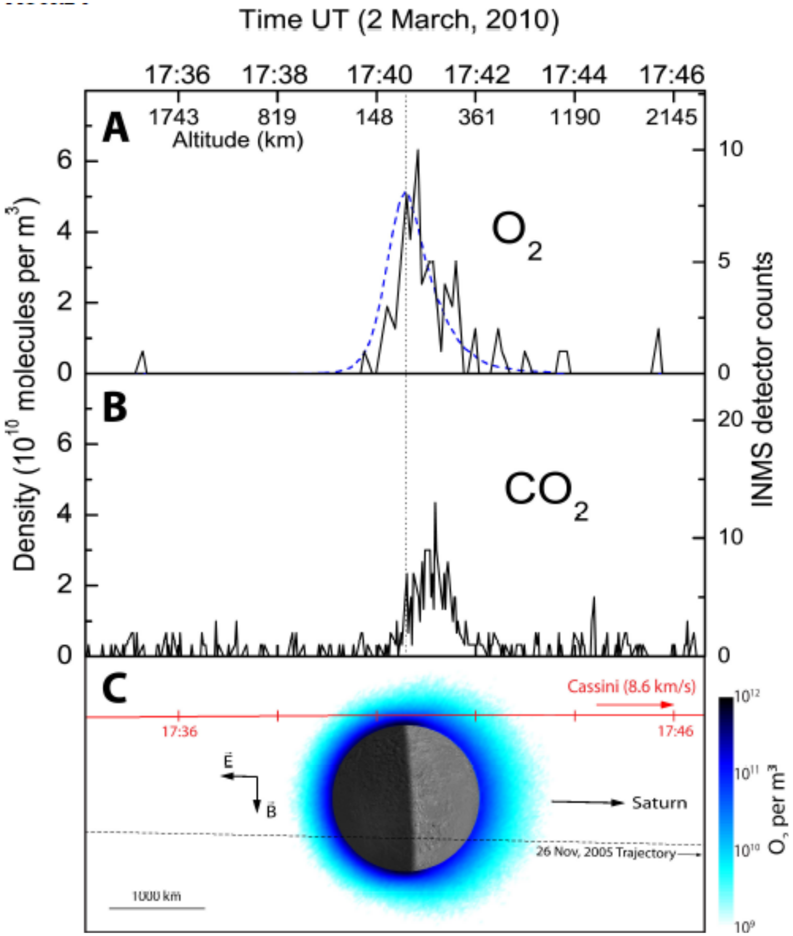
Negative ions in the plume

Coates et al., Icarus 2010, Faraday Discussions 2010

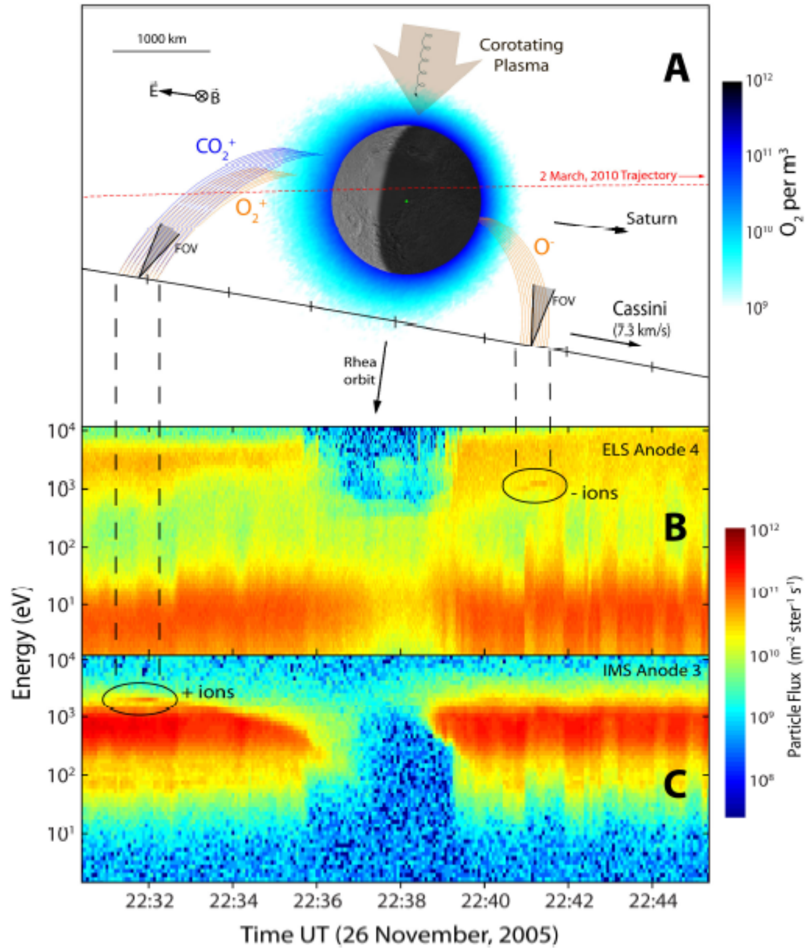
Rhea's O_2 and CO_2 atmosphere – from INMS and CAPS

Teolis, B.D., G.H. Jones, P.F. Miles, R. L. Tokar, B. A. Magee, J. H. Waite, E. Roussos, D.T. Young, F. J. Crary, A. J. Coates, R. E. Johnson, W.-L. Tseng, R. A. Baragiola

Science Dec 2010



In-situ neutral atmosphere measurements (INMS)



Negative and positive ions picked up from atmosphere pinpoint near-surface source (CAPS)

Future electron measurements at Mars

(i) Provide the locations of key plasma boundaries

(ii) Provide the unambiguous identification of ionospheric plasma in the tail of Mars

(iii) Identify regions of mixed ionospheric and solar wind plasma

(iv) Examine the role of magnetic anomalies and their plasma interaction

(v) Identify electron acceleration processes in Mars' environment

(vi) Complete the plasma context

Similar requirements at other unmagnetized objects – also be prepared for unexpected discoveries

Suggested electron spectrometer parameters for Mars:

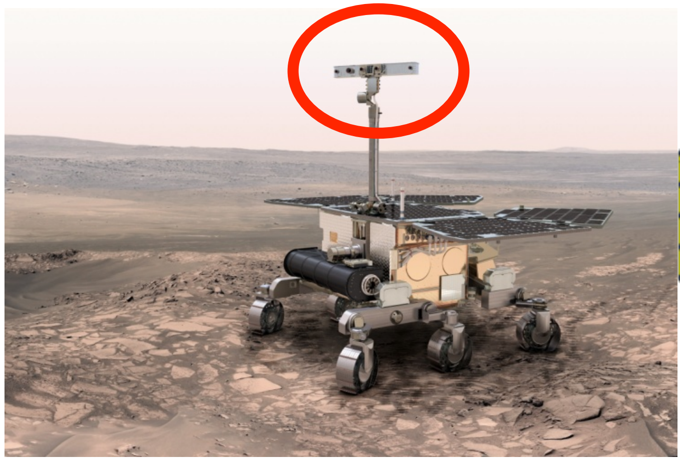
Energy range 0.6-2000 eV

Energy resolution ΔE/E 13%

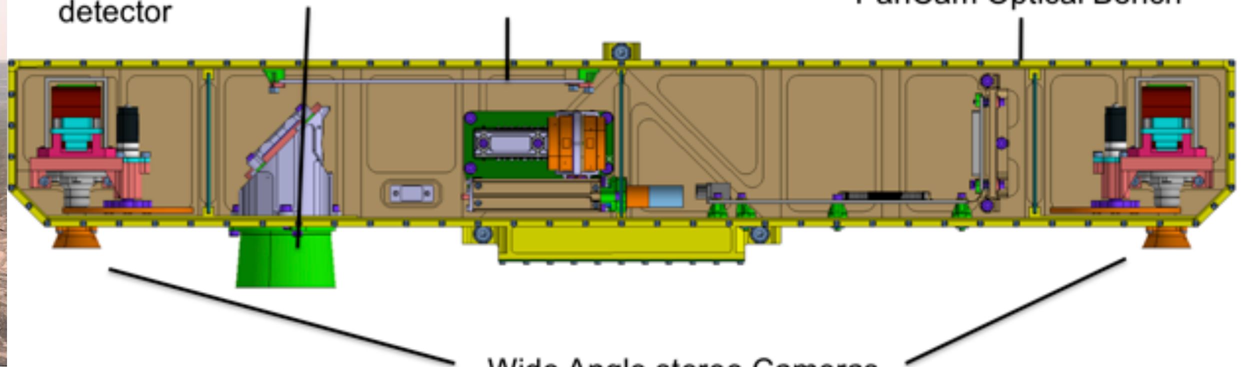
(ΔE/E=5% in range 0-100 eV)

Eyes of ExoMars 2018 rover: PanCam

PI: Andrew Coates MSSL-UCL
PM: Craig Leff MSSL-UCL
International team including DLR (D), Space-X (CH), Joanneum (A), Aberystwyth(UK) +US,…



Credit: ESA



PanCam includes:

- **Wide Angle Camera (WAC) pair**, for multi-spectral stereoscopic panoramic imaging
- **High Resolution Camera (HRC)** for high resolution colour images
- **Pancam Interface Unit (PIU)** to provide a single electronic interface
- **PanCam Optical Bench (POB) to house PanCam** and provide planetary protection

Main objectives:

- Locate landing site, rover position with respect to local references
- Support rover track planning
- Provide context information on the rover and its environment.
- Geologically investigate and map the rover sites.
- Study the properties of the atmosphere and variable phenomena.

- Nagy, A.F., et al., The plasma environment of Mars, SPACE SCIENCE REVIEWS Volume: 111 Issue: 1-2 Pages: 33-114, 2004.
- Lundin, R., et al., Solar wind induced atmospheric erosion at Mars – first results from ASPERA-3 on Mars Express, Science 305, 1933-1936, 24 Sep 2004.
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