Coupling between the Martian atmosphere, ionosphere, and magnetosphere

Solar forcing and escape mechanisms

Rickard Lundin, IRF, Sweden

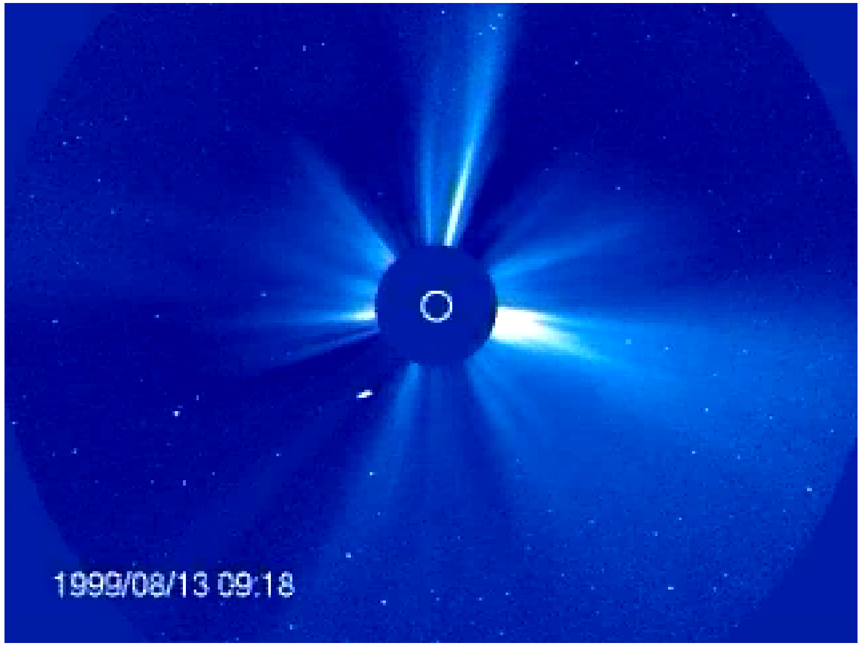
1. *Solar forcing*
2. *The Martian interface to space - atmosphere and ionosphere*
3. *Solar forcing and the magnetosphere, ionosphere, atmosphere coupling*
4. *Planetary ion and neutral particle escape*
5. *Solar impact on the atmospheric evolution*

1. Solar forcing

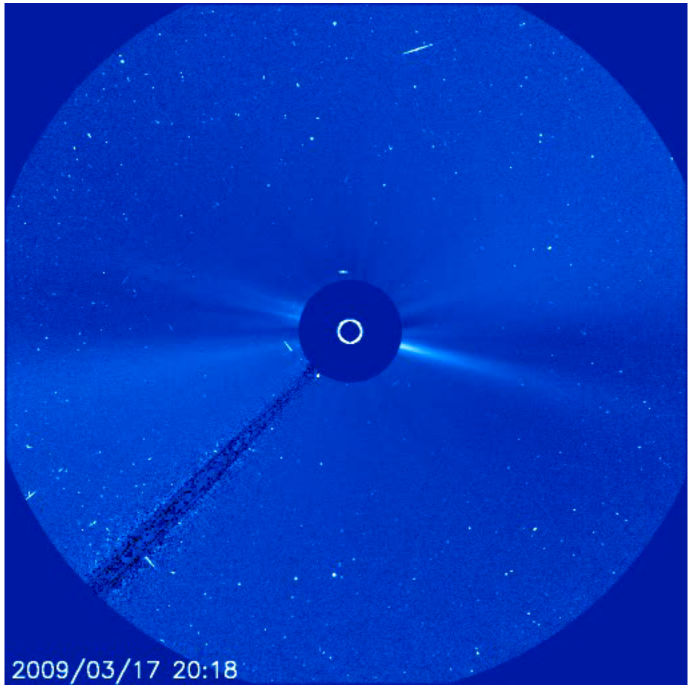
- The Sun is (and has been) a pretty stable star
- Although its properties have changed significantly on the longest timescales (nuclear evolution)…

Emissions of the Sun related with activity show strong variability

Emissions tell us how the Sun works, but the emissions also have a strong impact on the planets in the solar system.



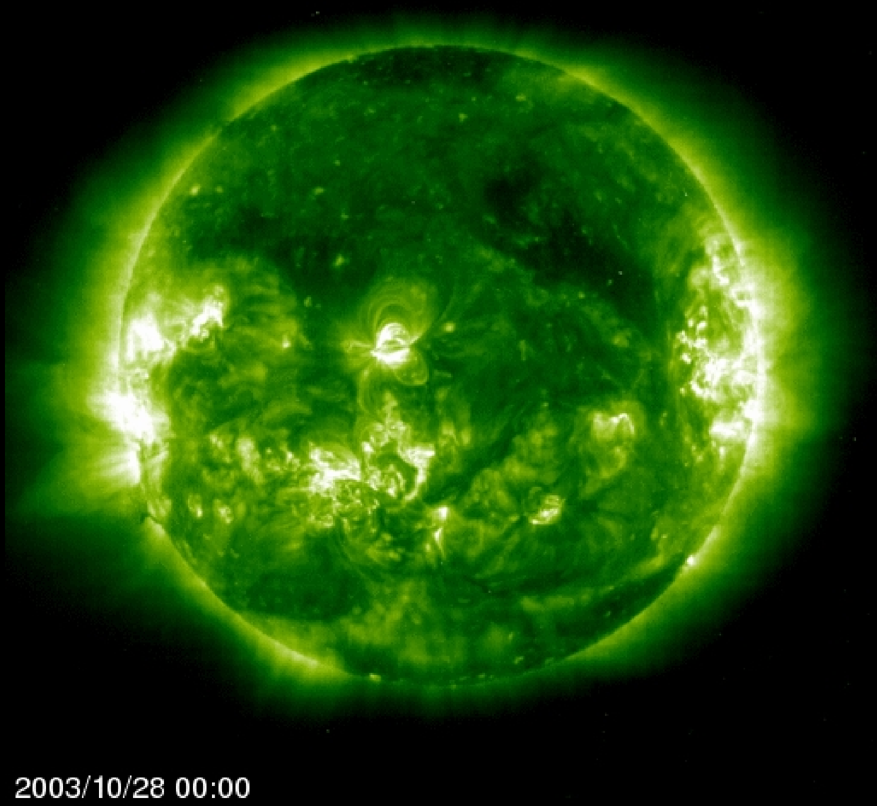
Solar maximum (SOHO LASCO, ESA/NASA)



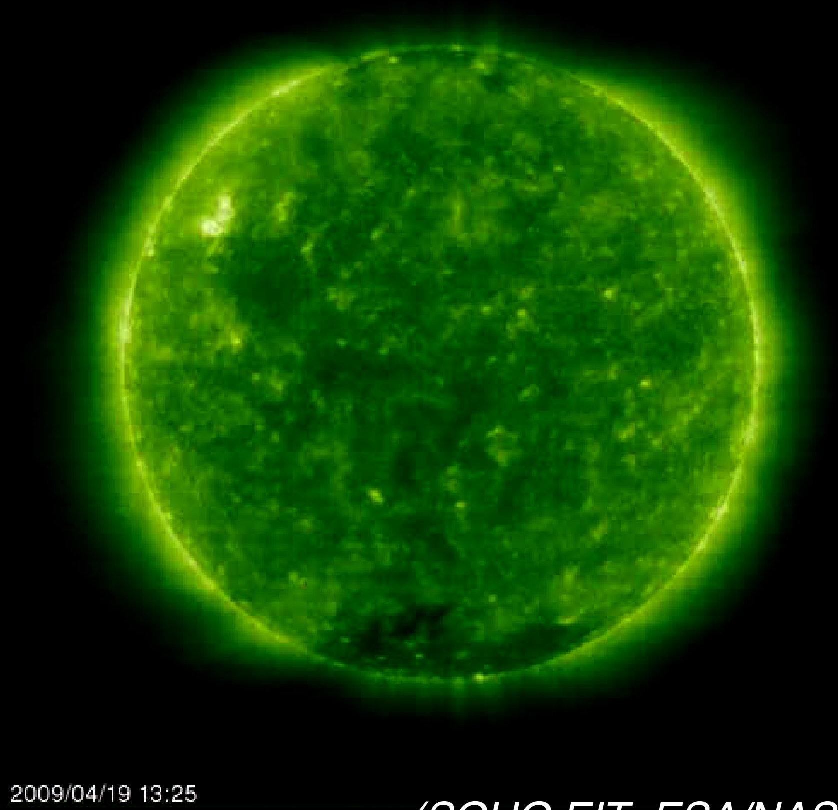
Solar minimum (2009)

The Sun in UV (195 nm)

Solar maximum
October 2003

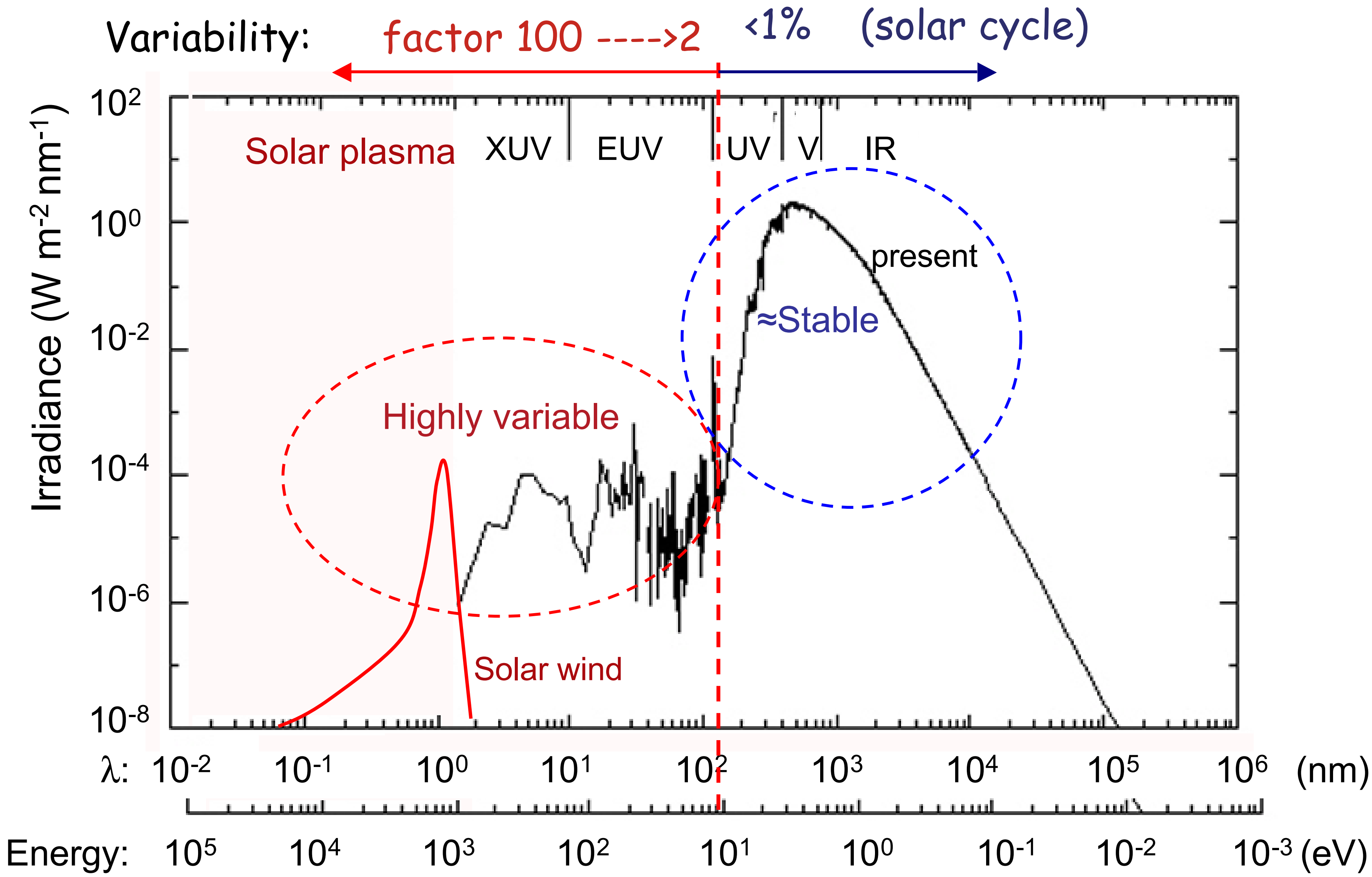


Solar minimum
20-23 April 2009



(SOHO EIT, ESA/NASA)

Solar variability



Solar forcing - effects on planets

Solar forcing of planetary atmospheres (+ comets) is related with heating/ionization + energy and momentum transfer

Heating:

- Sum of irradiation

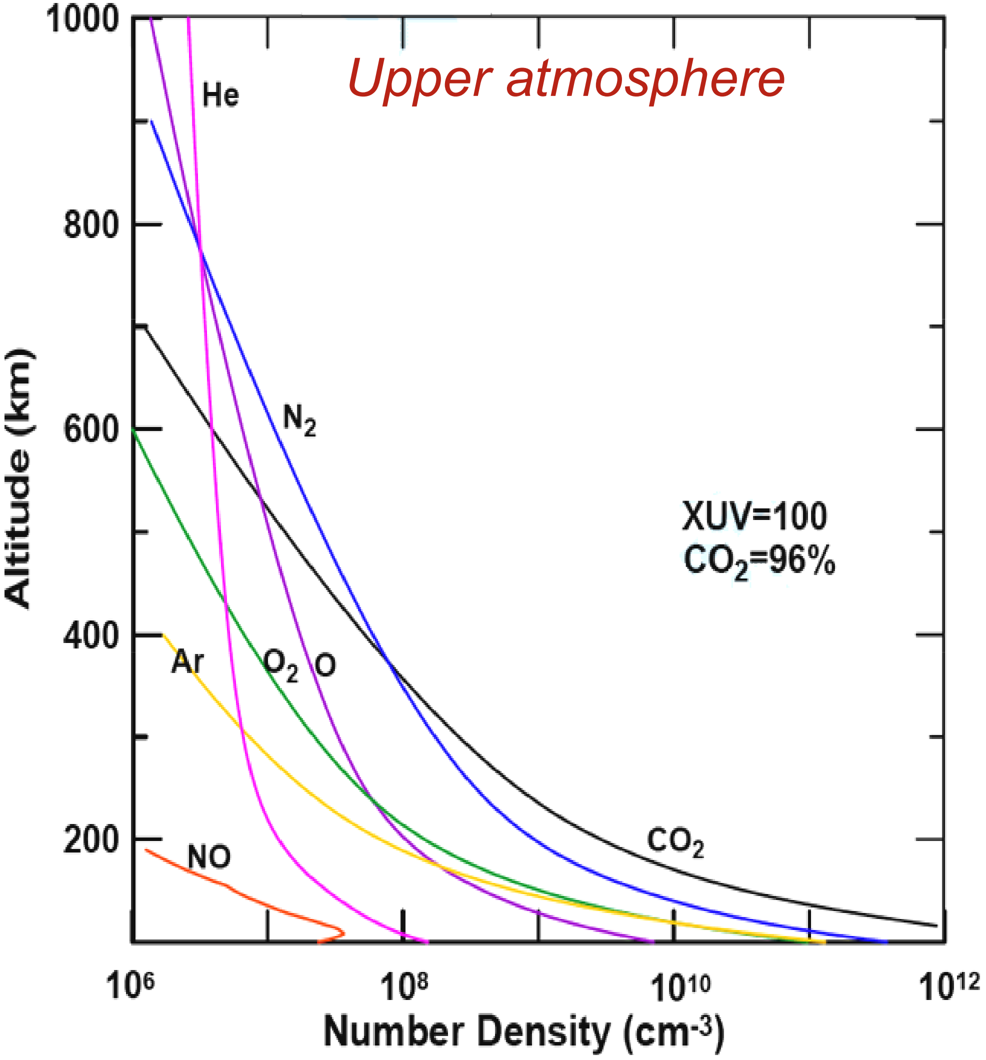
Ionization :

- FUV/EUV radiation
- Impact ionization, ENA/charge exchange, CIV….

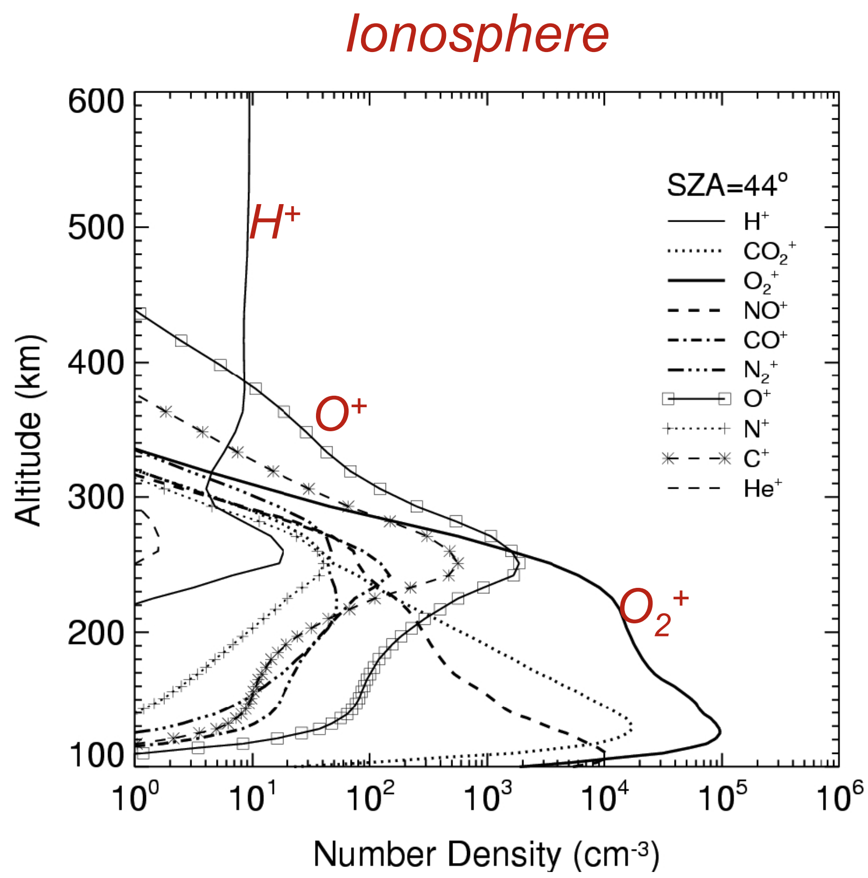
Energy and momentum transfer:

- Solar wind plasma + ENA
- Solar wind electric field
- ULF waves

2. The Martian interface to space - atmosphere and ionosphere



(Shinagawa and Cravens, 1989)

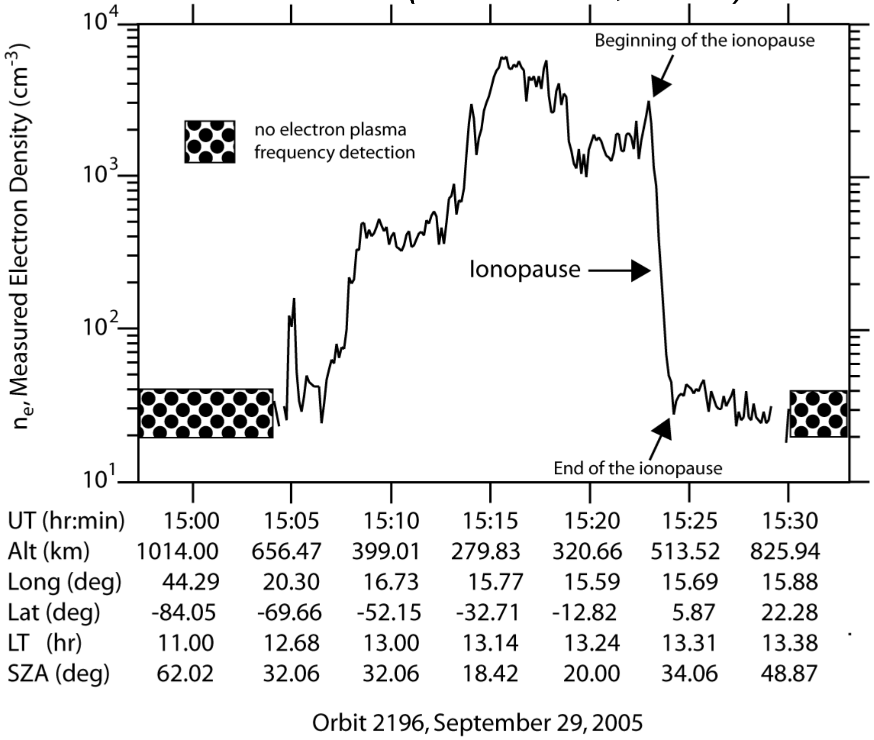


(Terada et al, 2009)

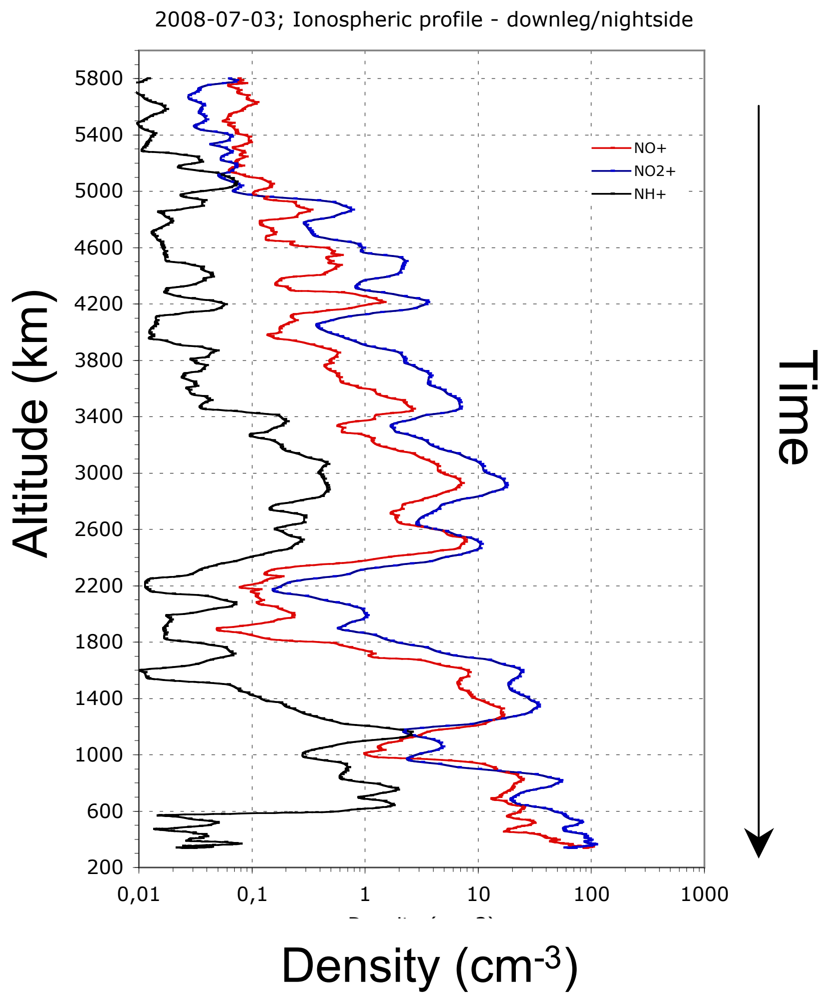
Ionosphere of Mars

- Extension into space
- Composition
- Interaction with magnetosheath plasma
- Variability

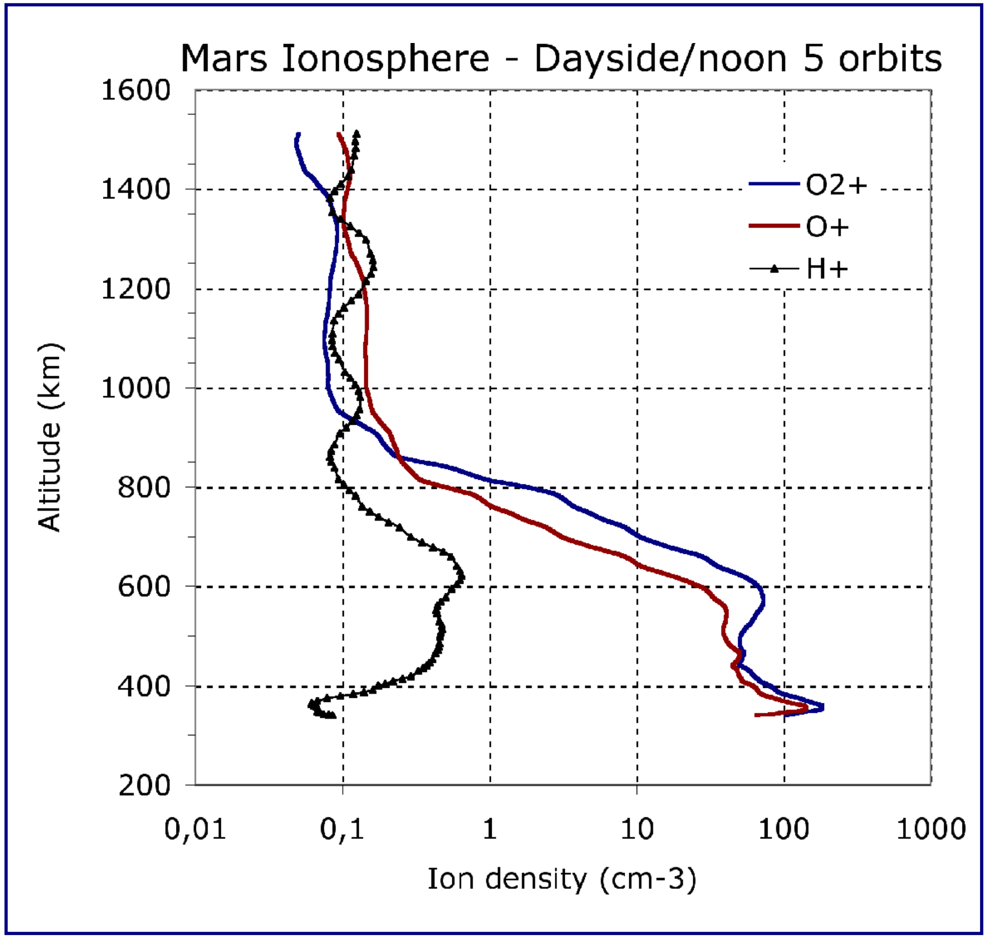
MARSIS *(Duru et al., 2008)*

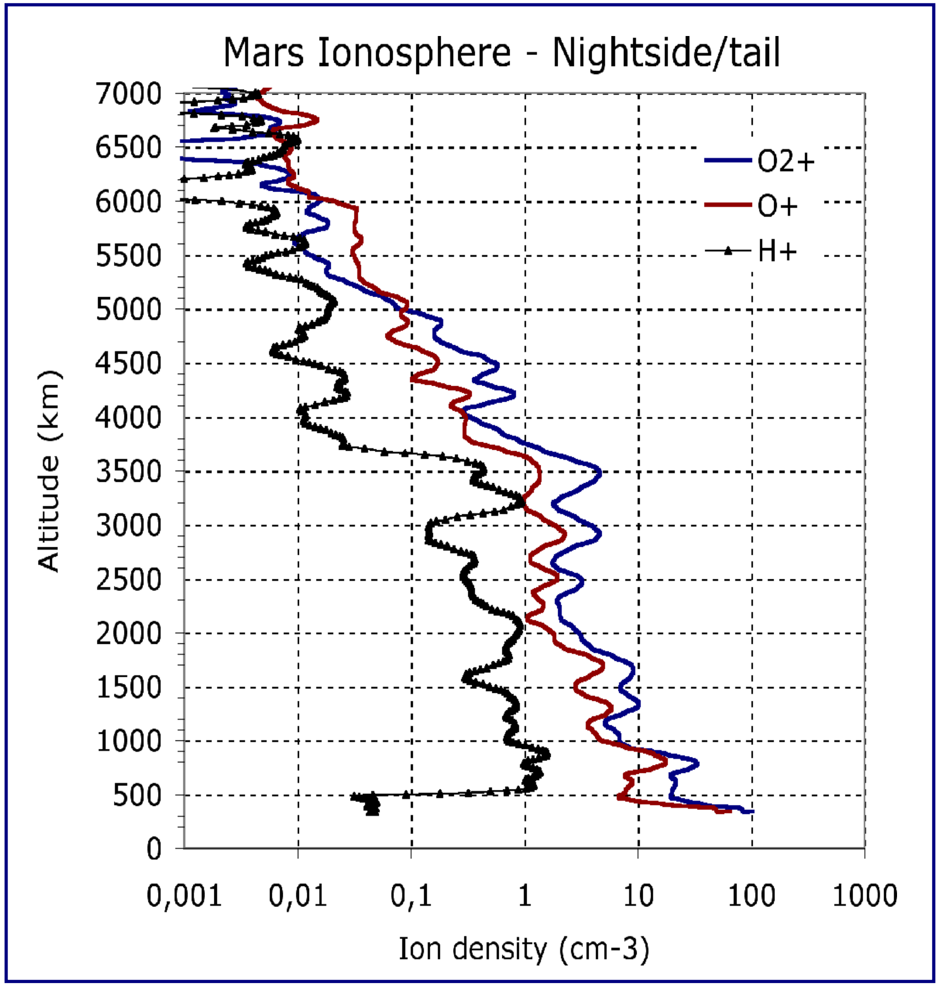


Variability - temporal (consistent with MARSIS)



Mars Ionosphere - average composition and density profile





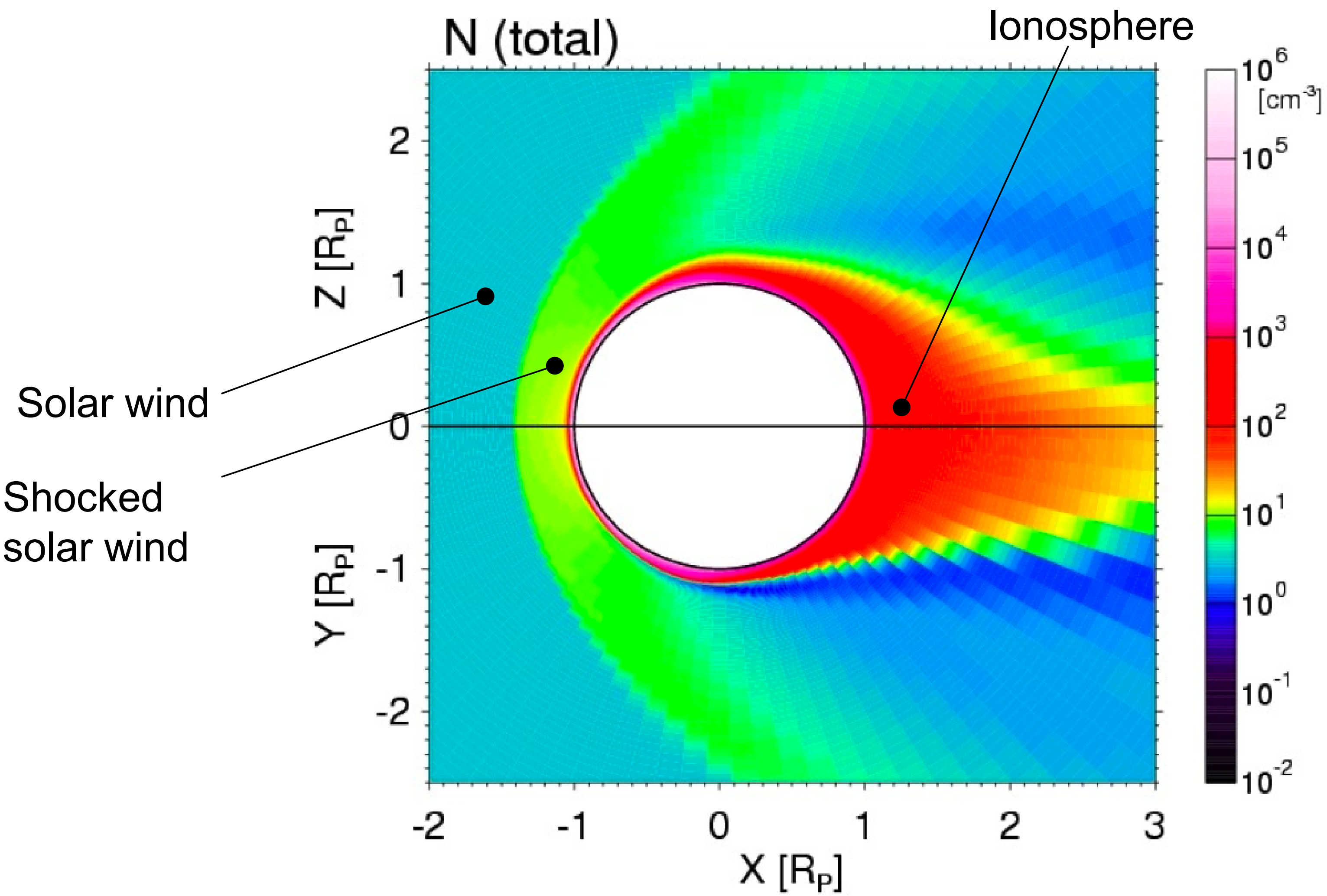
Dayside/noon:

- Sharp density drop (MPP/IMB)
- Weak dominance of O_2^+ vs O^+ at low altitudes

Nightside:

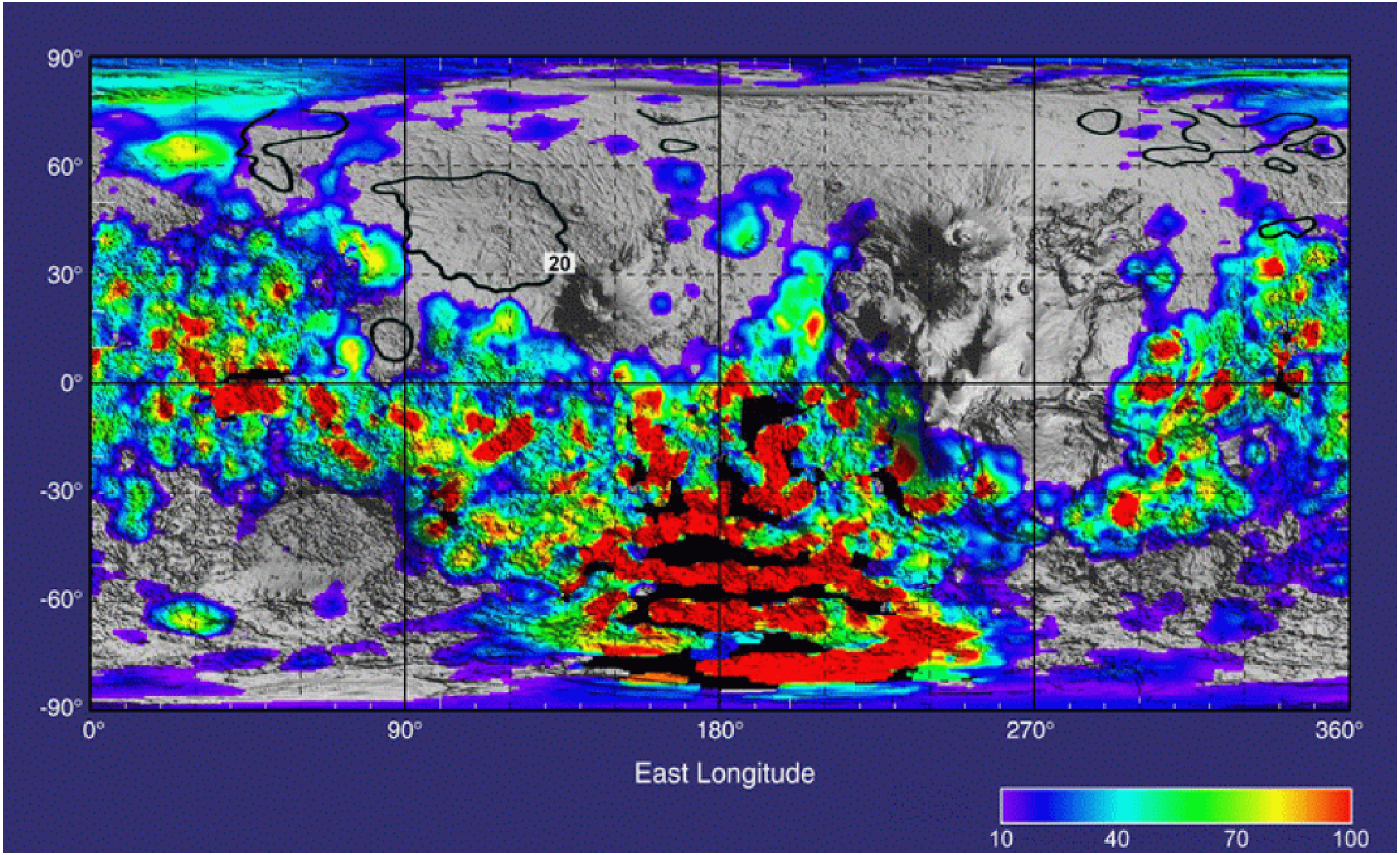
- Gradual density decrease
- Density variability (ULF waves)

Modeled ion density - ionospheric extension into space



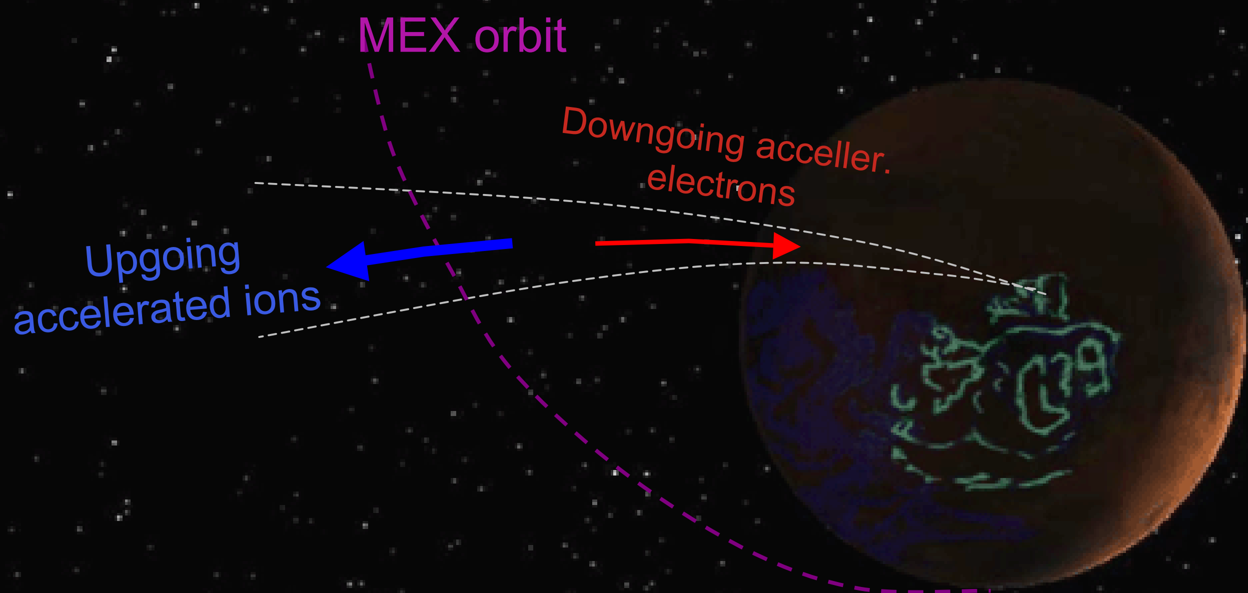
(Terada et al, 2009)

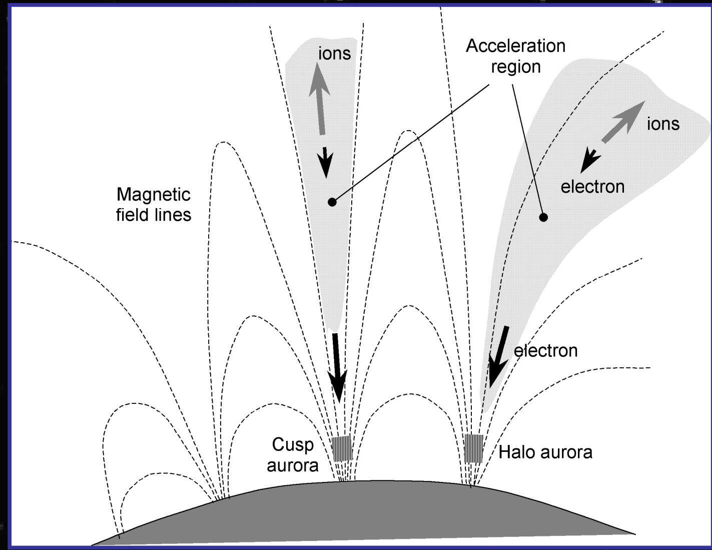
Implications of the crustal magnetic field at Mars (B @ 170 km)

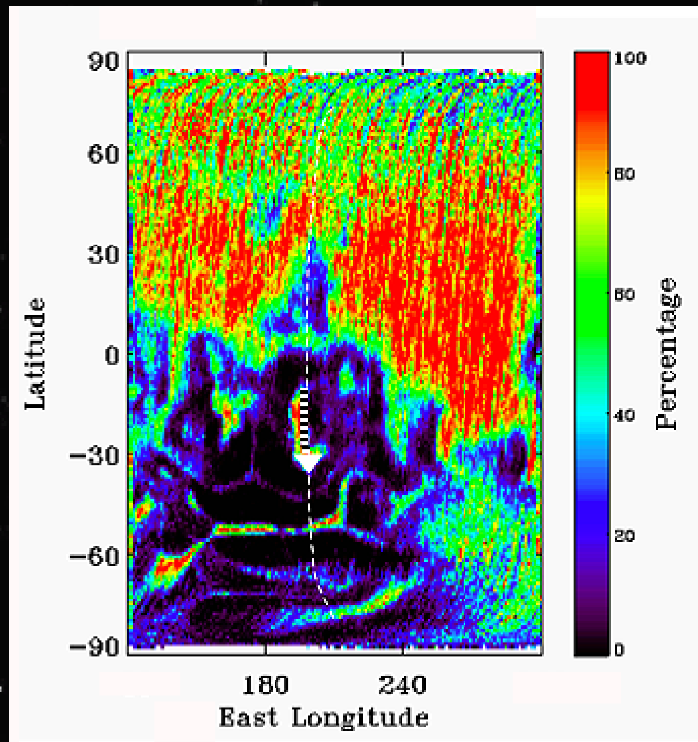


(Mitchell et al., Lunar and Plan. Science, 2005)

Aurora above magnetic anomalies at Mars

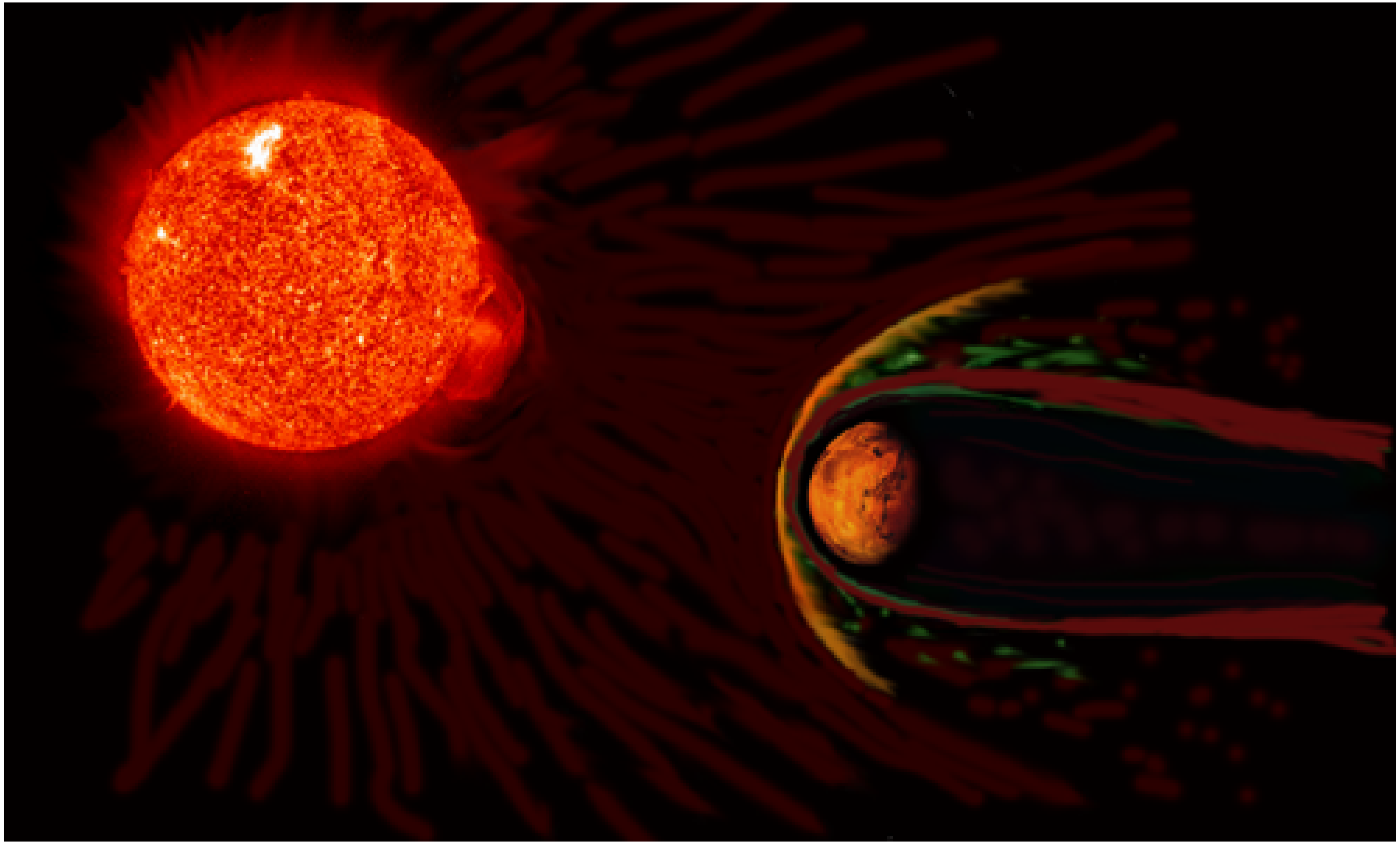






- *Magnetic cusps connected to Mars*
- *Electron/ion acceleration (Earth´s auroral oval) (Lundin et al, Science, 2006)*
- *Auroral emissions discovered by SPICAM (Bertaux et al, Science, 2005)*

2. Solar forcing and the magnetosphere - ionosphere - atmosphere coupling



Loss of water from mars - The result of solar forcing ?

Solar forcing leads to mass-loss from unmagnetized objects near the Sun

FUV/EUV heating —> expansion
EUV ionization —> plasma
Solar wind —> fast removal

Dusty plasma tail
($N_{neutral}/N_e$ >10^{-6})

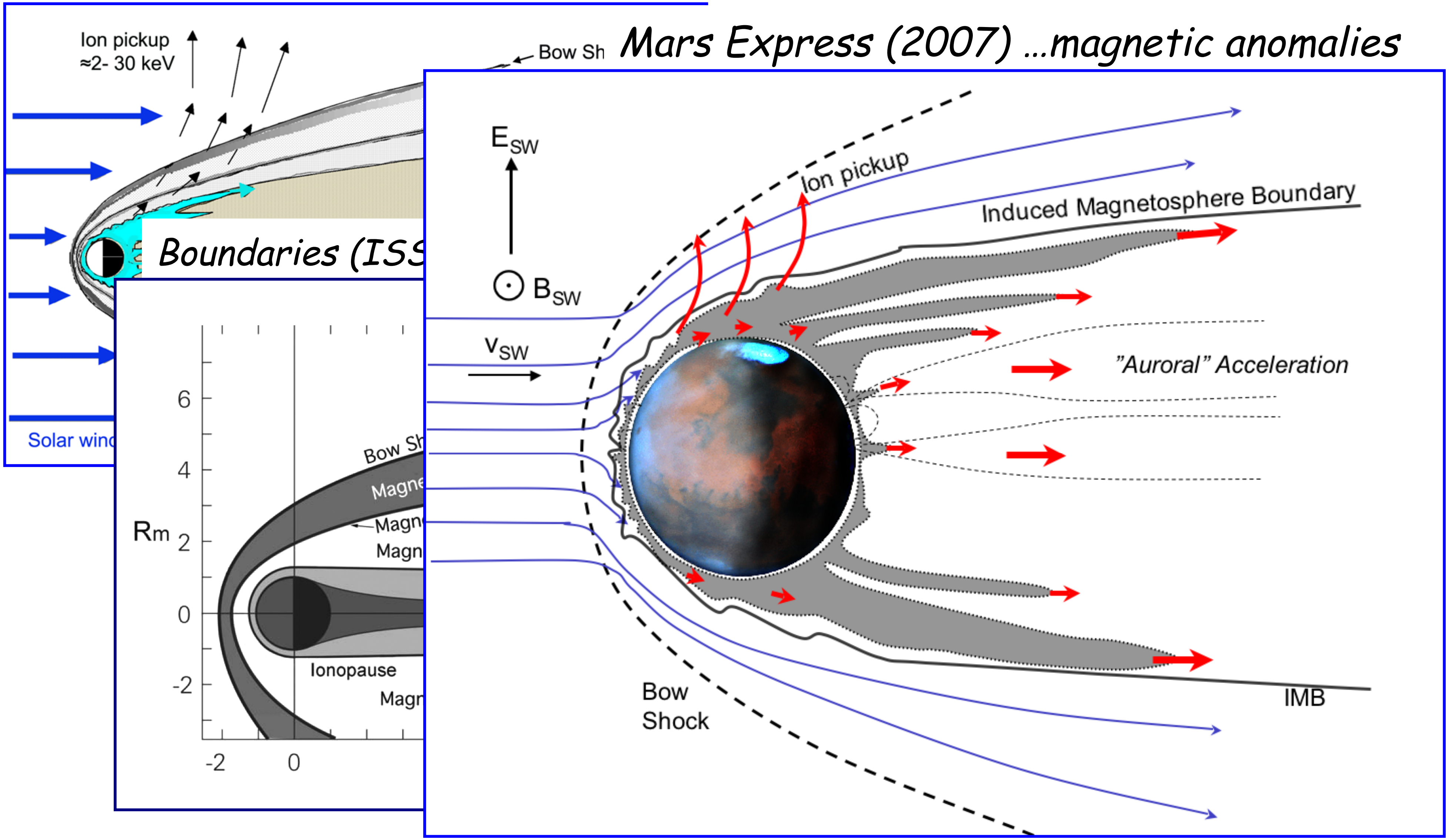
Plasma tail proper
(ion tail)

Note: A kilometer size comet may loose 10-100 kg/s of volatiles at distances ≈1 AU from the Sun

The Martian induced magnetosphere

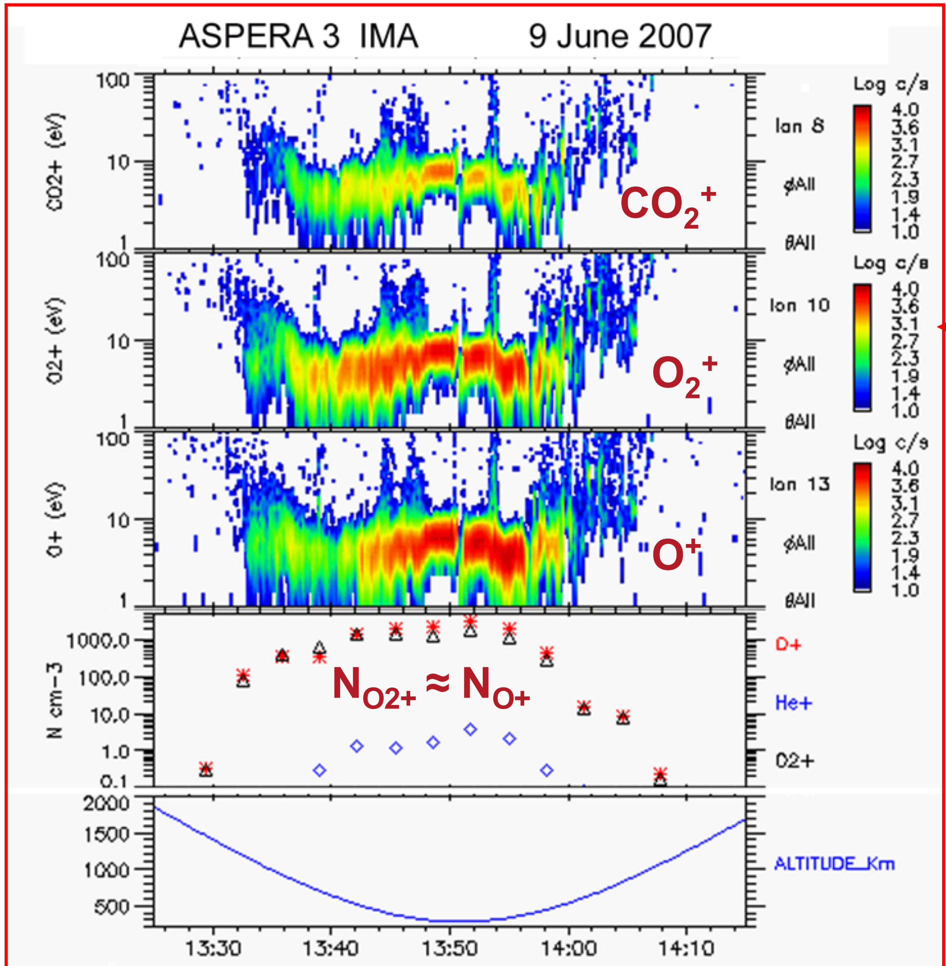
Phobos-2 (1990) Cometlike-like outflow

Mars Express (2007) …magnetic anomalies



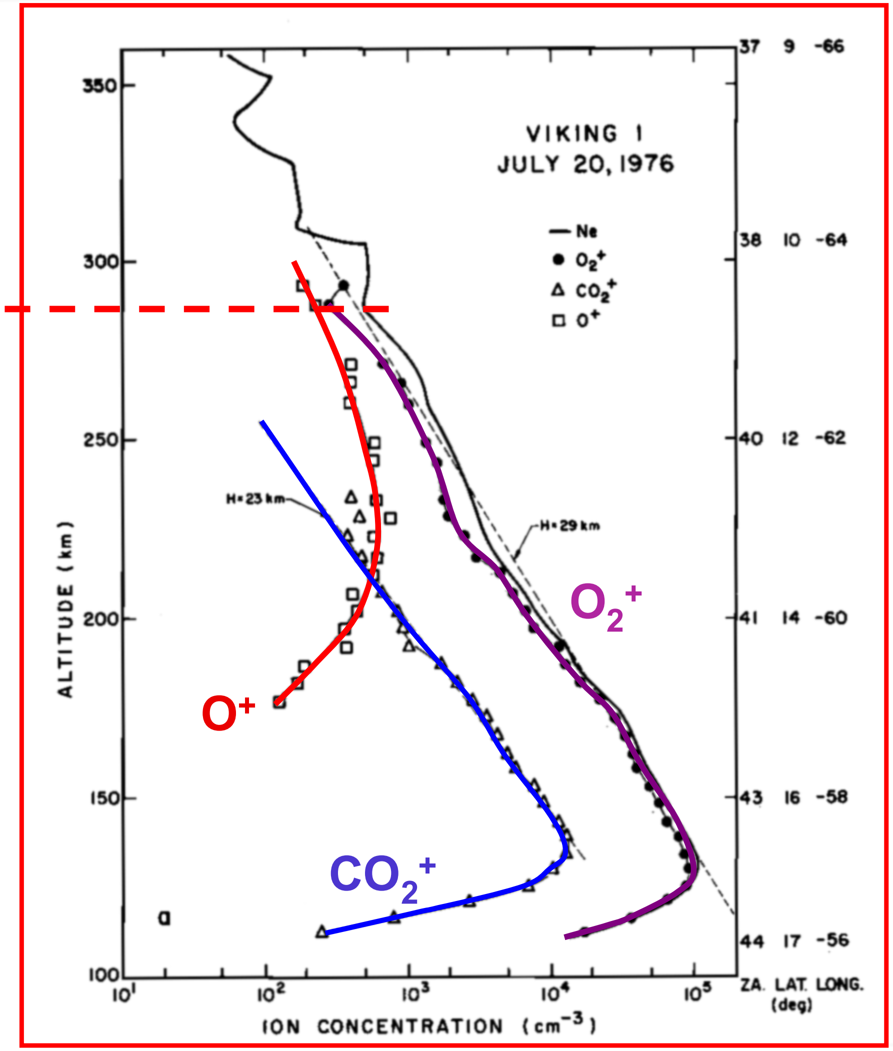
The "floor" of the Martian ionospheric ion outflow

Planetary heavy ions < 100 eV



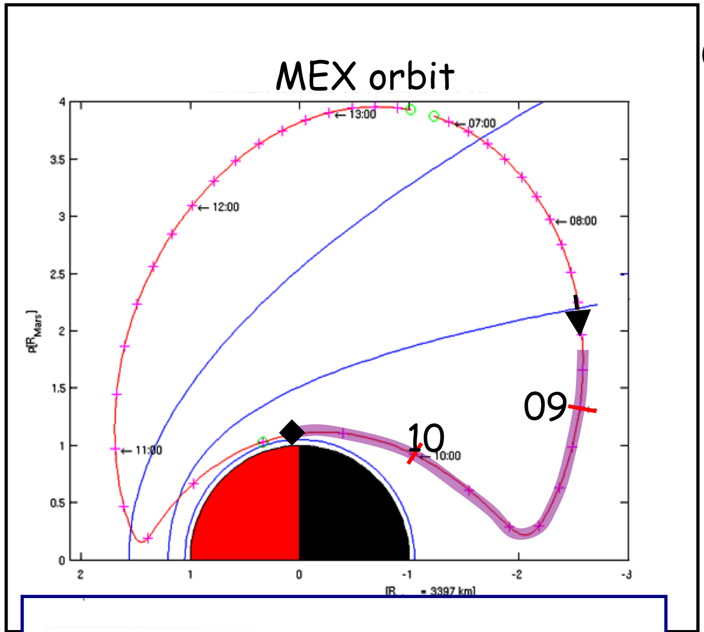
Note: 2-3 min flux modulations (ULF waves)

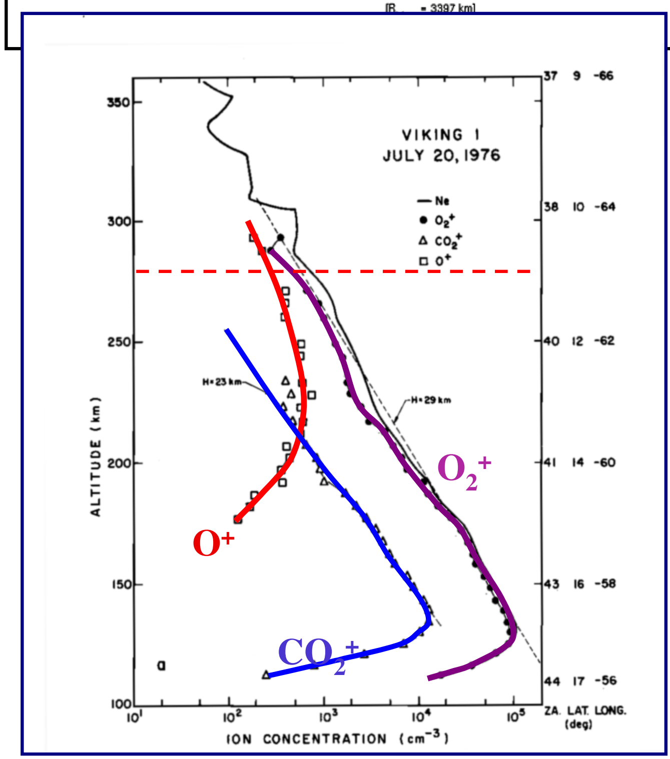
$N(O_2^+) \approx N(O^+) > N(CO_2^+)$ => H≈300 km

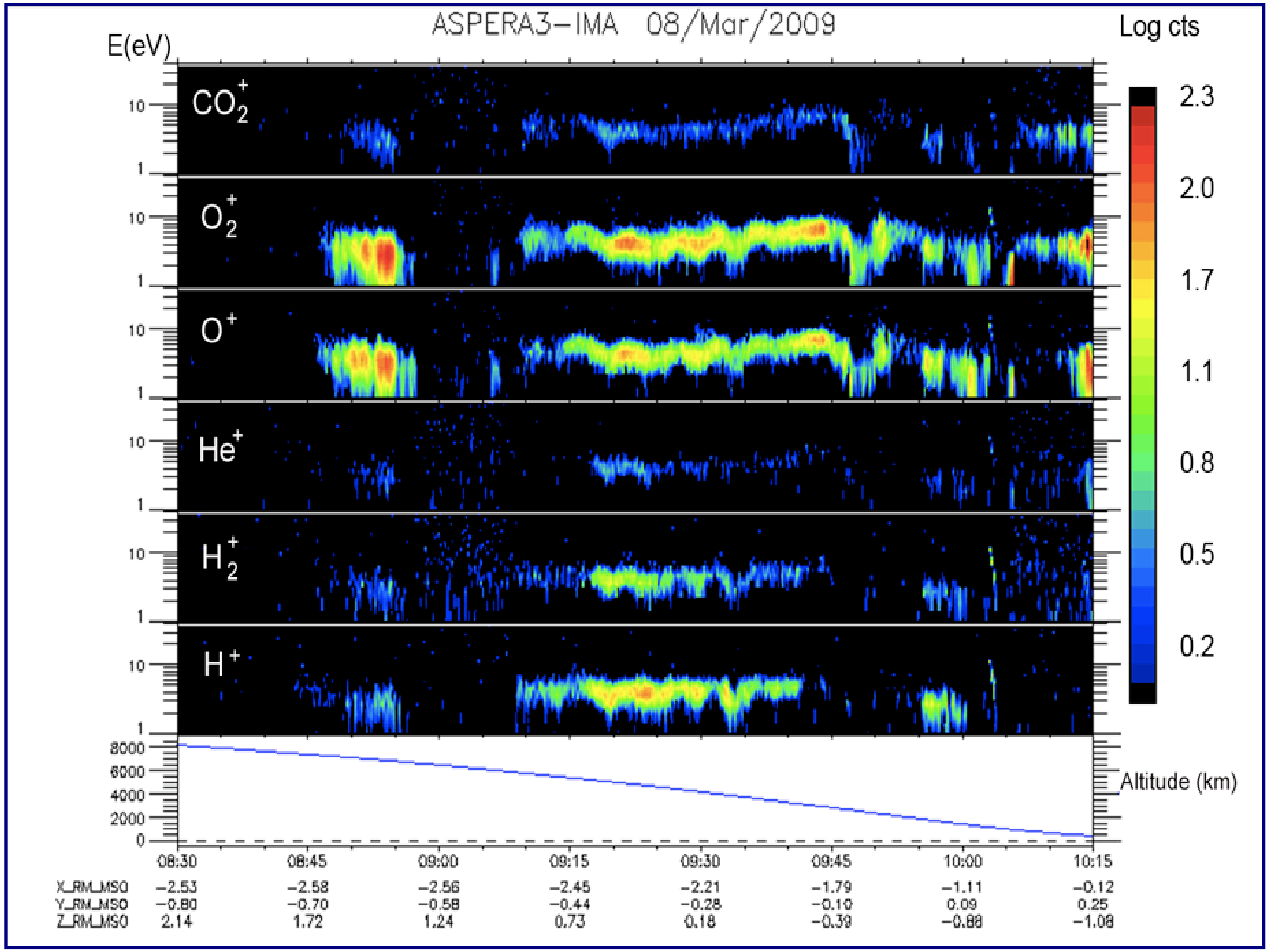


(Hanson et al., JGR, 1977)

Composition of cold ion escape into the Tail

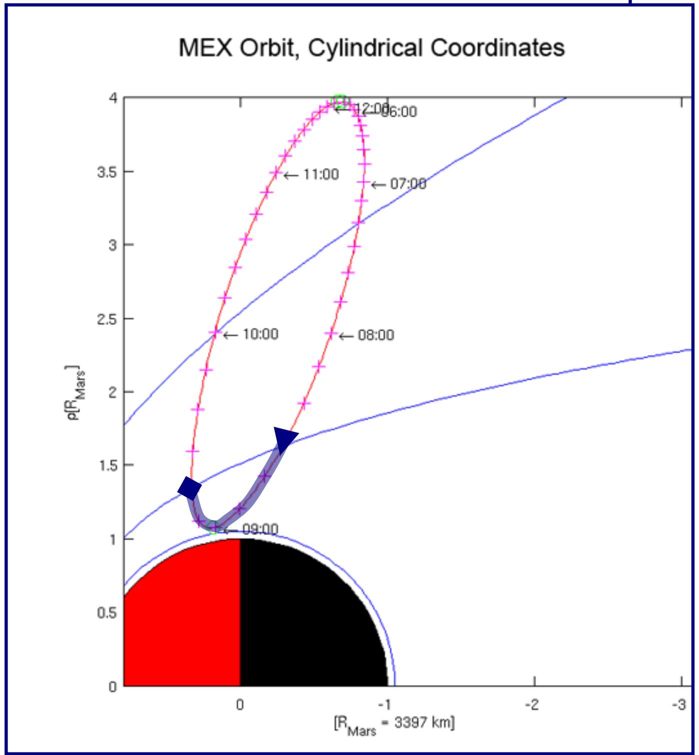


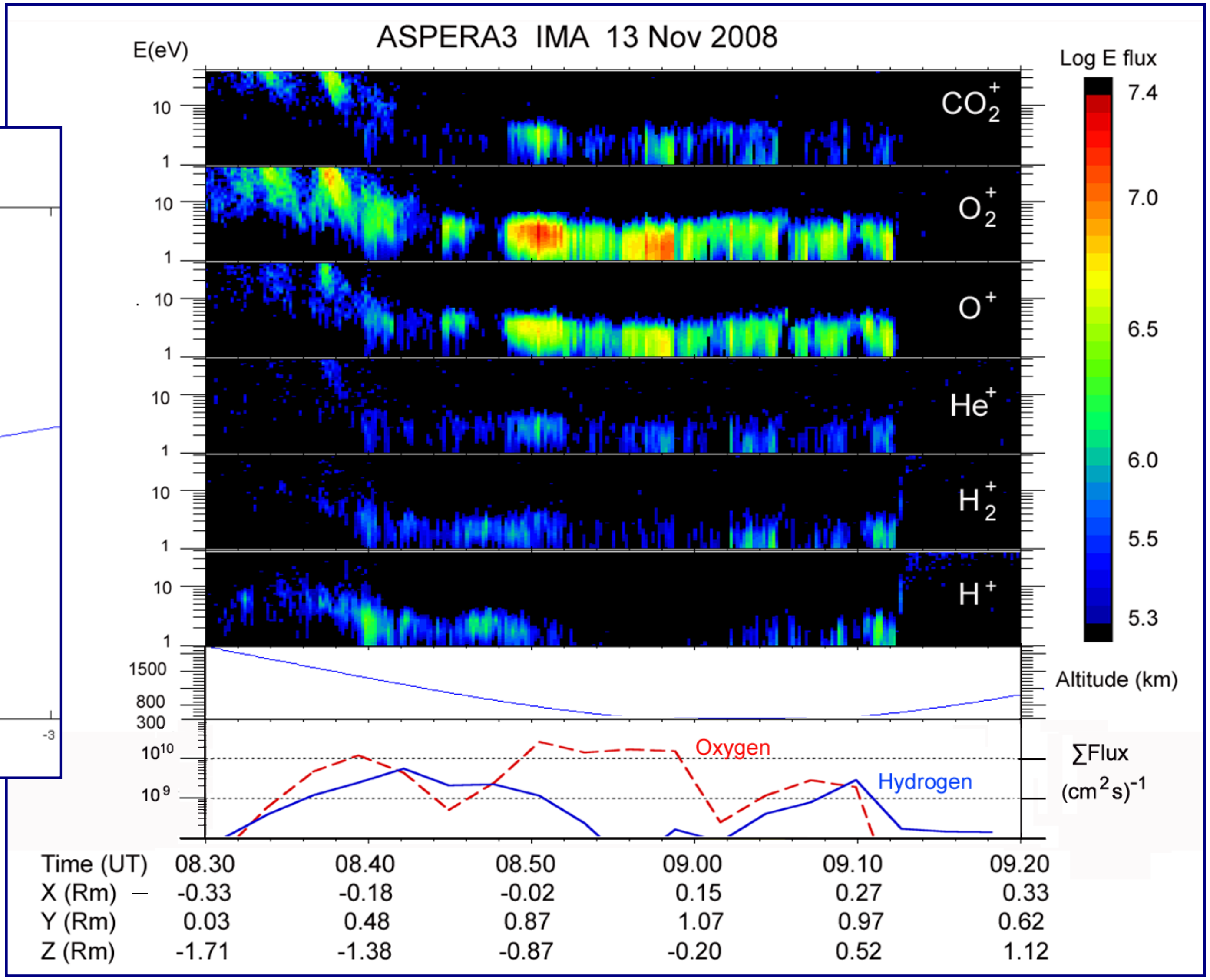




- Ion outflow composition => extraction at low altitudes
- Hydrogen ion outflow most pronounced in the tail wake
- Tail sometimes "filled" with outflowing cold ions

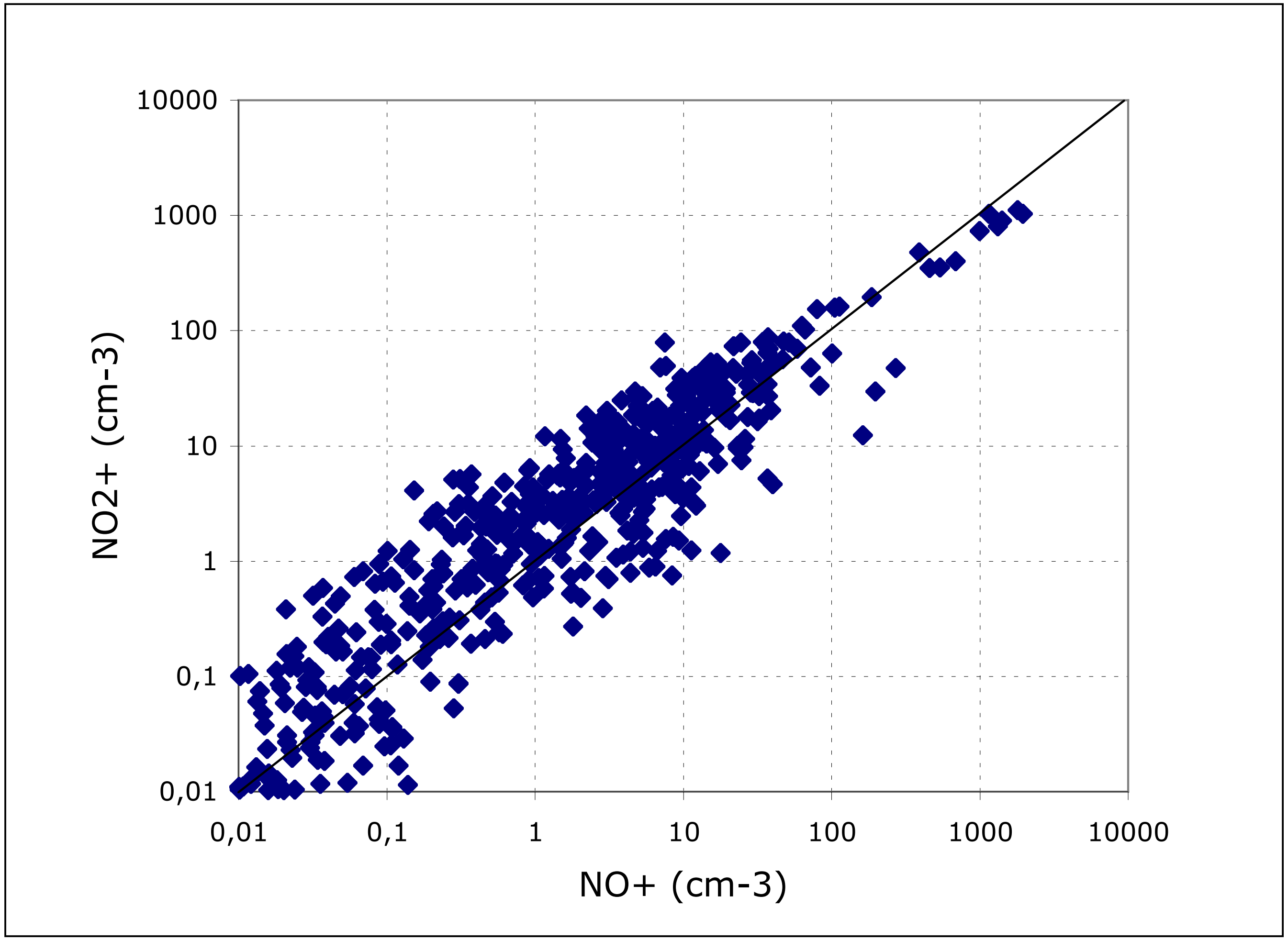
Cold Ion Outflow and Composition - Terminator





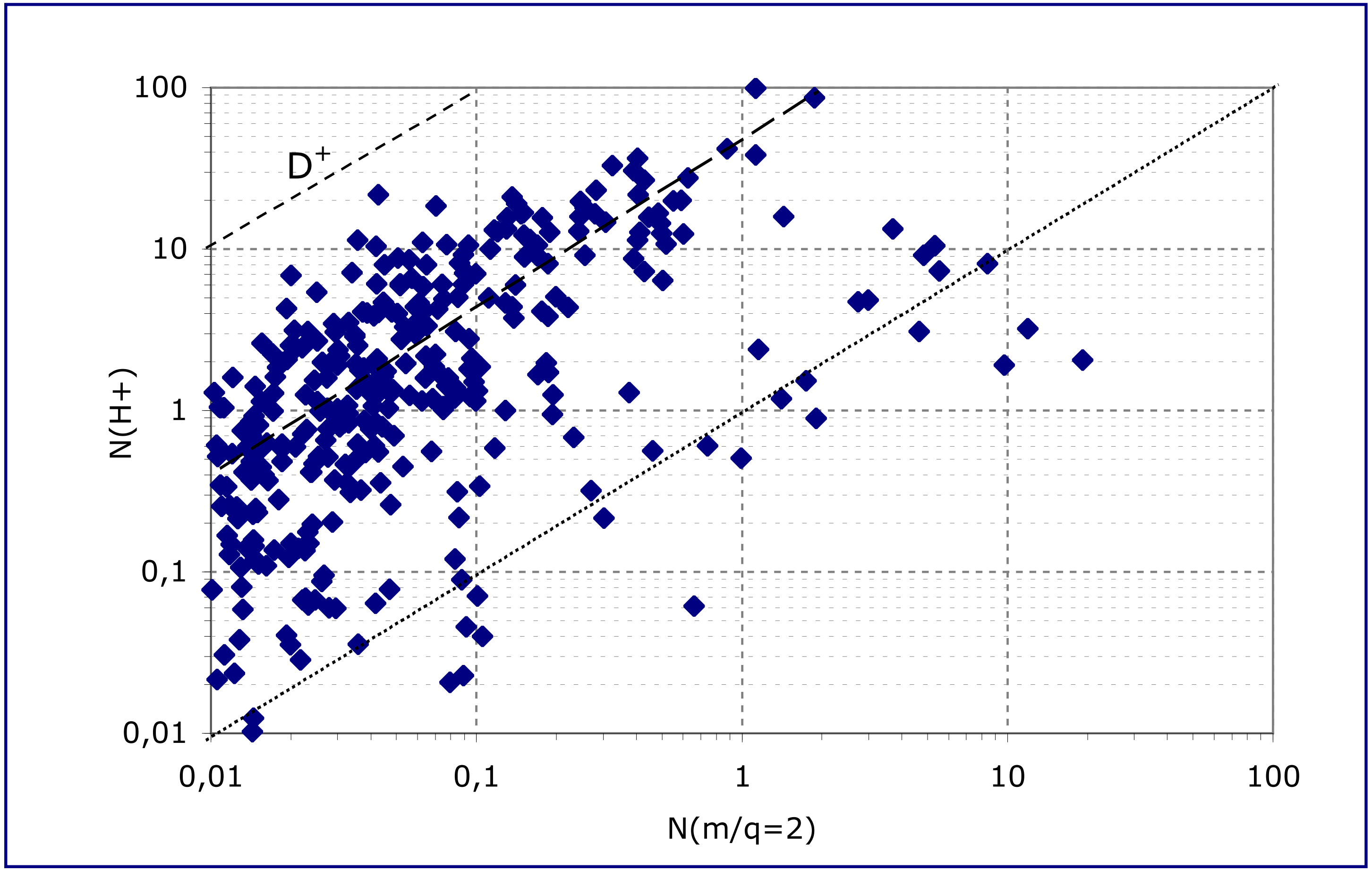
Note: Hydrogen ions only found at altitudes >400 km

Outflowing ion number densities, O^+ vs O_2^+



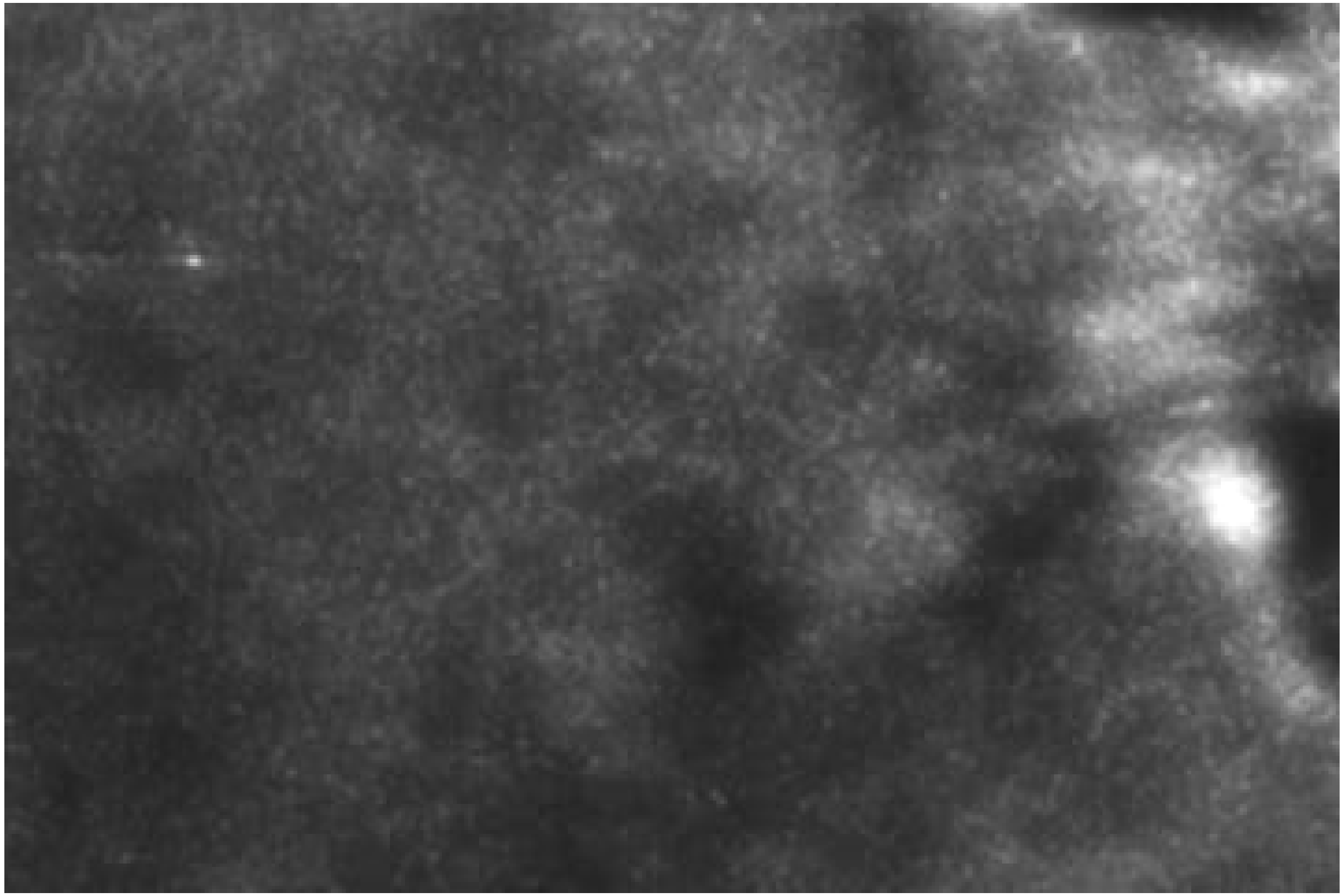
- Simultaneous measurement leads to scatter up to ≈10 (density modulated by waves)
- Average density ratio close to one - somewhat higher abundance (≈2) of O_2^+

$N_{M/q=2}$ / N_{H+} number density ratio H_2^+ or D^+ ?



(m/q=2 / H^+) ratio ≥$2\cdot10^{-2}$. D/H ratio in Martian atmosphere ≈10^{-3} (e.g. Krasnopolski, 2001) => H_2^+ rather than D^+

3. Solar forcing and the magnetosphere, ionosphere, atmosphere coupling



Planetary ion and neutral particle escape

1. **Thermal escape** (inferred/modelled)

- Jeans escape, driven by EUV and XUV heating
- Hydrodynamic escape, consisting of a bulk expansion of the upper atmosphere due to intense solar EUV/XUV fluxes

2. **Nonthermal escape** (can be measured)

- Photochemical escape, associated with dissociative recombination
- Ion sputtering produced by ions impacting the upper atmosphere/corona
- Ionospheric plasma energization and escape driven by solar wind forcing
- Ionospheric ion pickup by the solar wind motional electric field

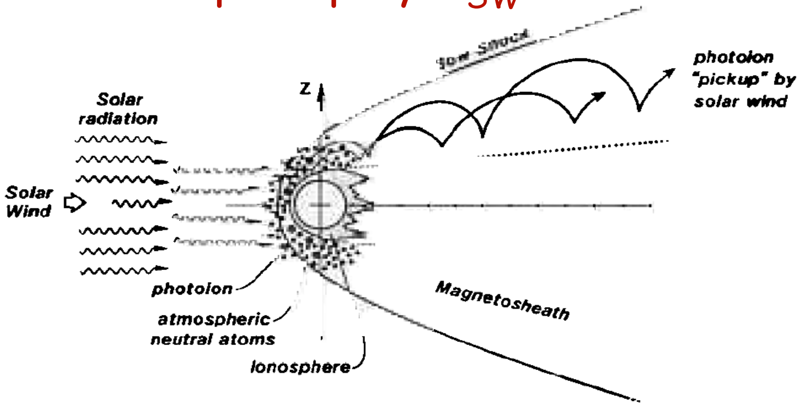
(e.g. Chassefiere et al., 2007)

Plasma acceleration

1. Direct energy and momentum transfer (Perez de-Tejada, 1987)

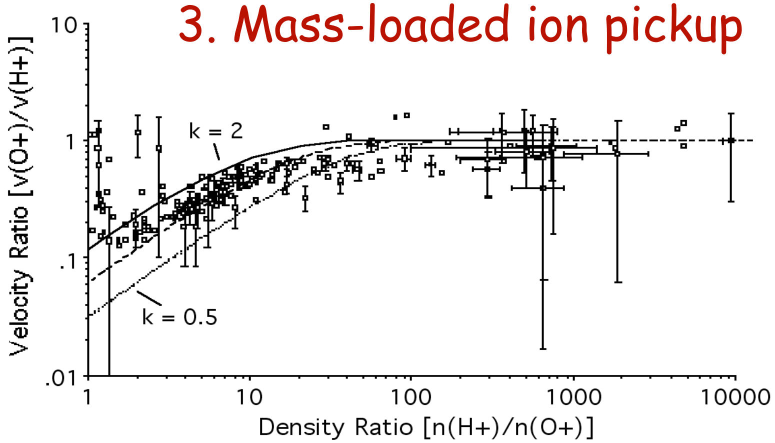
$$\Phi_M = \frac{v_{SW} m_{SW}}{v_M m_M} \left(\Phi_{SW} - \frac{v_{i,SW}}{v_{SW}} \Phi_{i,SW} \right) \frac{\delta_{SW}}{\delta_M}$$

2. Ion pickup by E_{SW}



(Luhmann et al., 1990)

3. Mass-loaded ion pickup



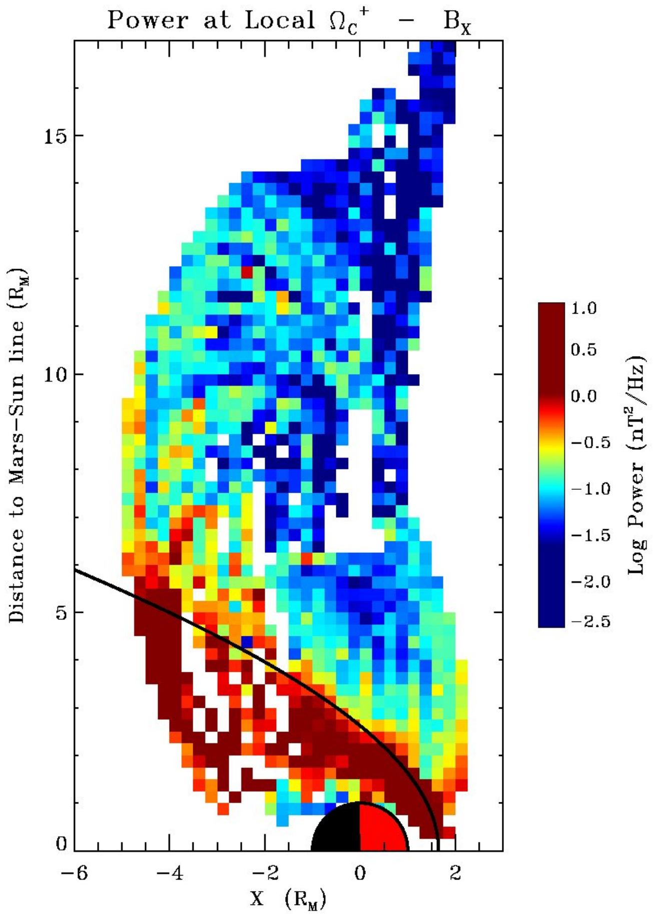
(Lundin and Dubinin, 1992)

4. Wave acceleration (Ponderomotive forcing)
5. Parallel E-field / ambipolar diffusion
6. Current sheet acceleration, JxB

Which processes is most important, where, and when?

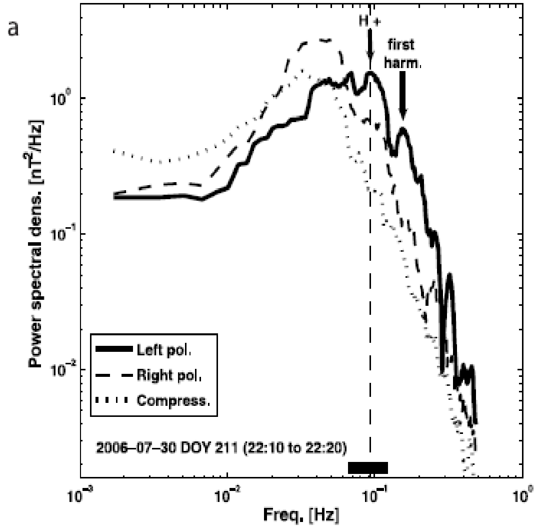
Waves: generation, propagation, and implications for ionosphere and m-sphere

- Omnipresent inside induced m-sphere



- Cyklotron frequency
- Wave modes?

(Delva et al., 2007)



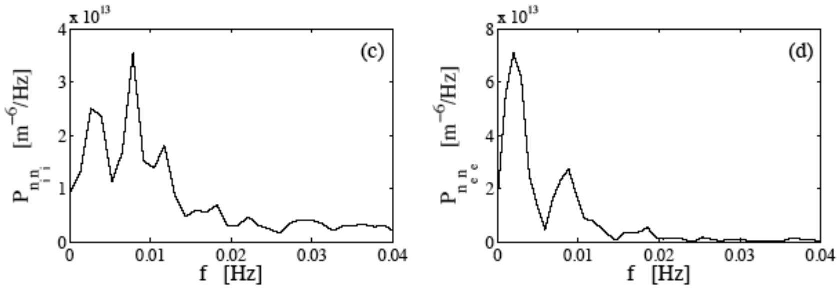
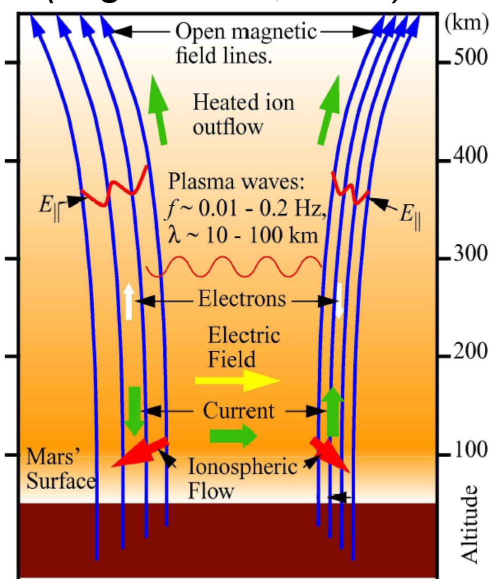


Figure 3. (a) Ion density; (b) electron density; (c) power spectral density of the ion density; and (d) power spectral density of the electron density.

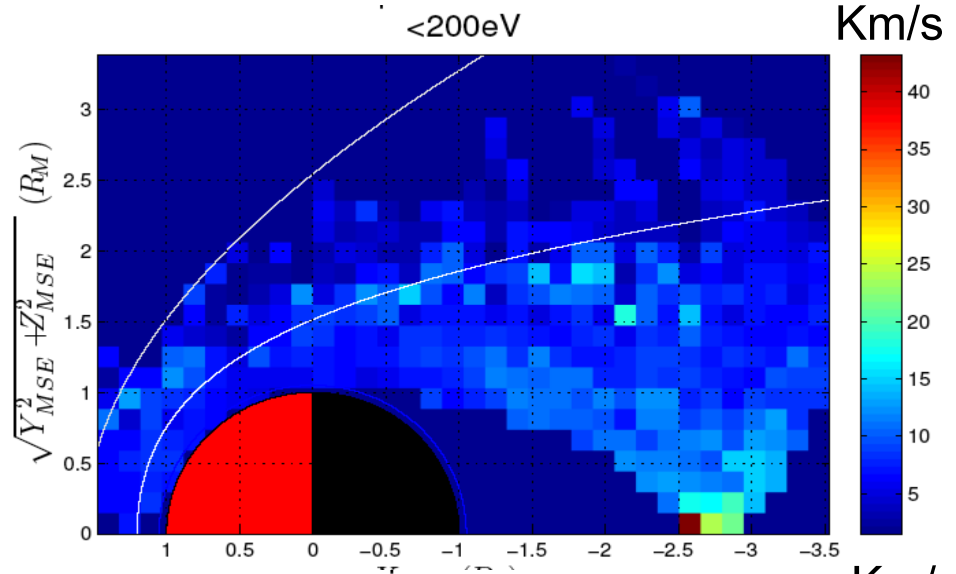
(Gunell et al., 2007)

- Plasma acceleration

(Ergun et al., 2005)



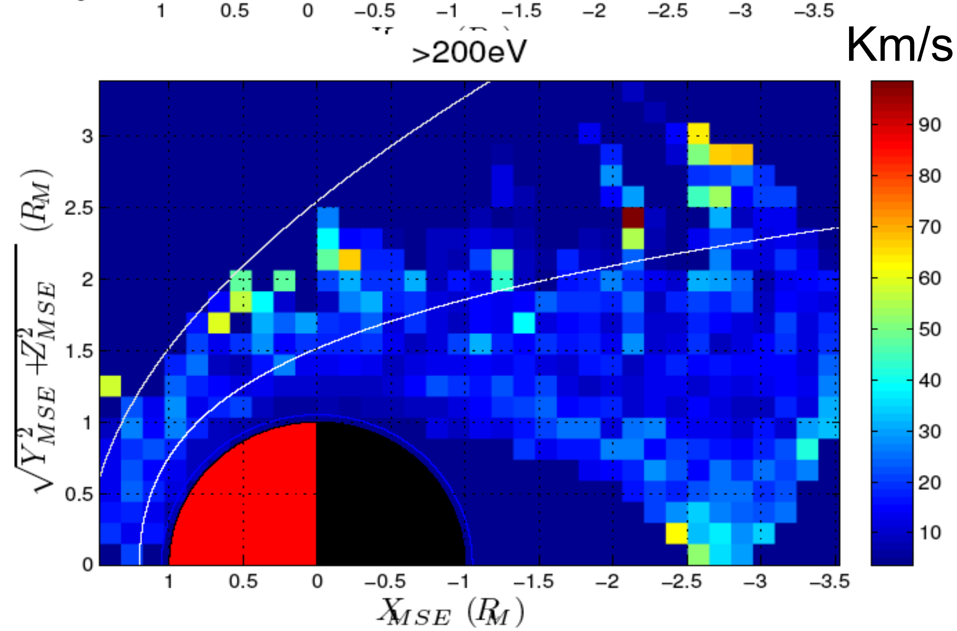
Low-energy, comet-like ionospheric outflow from Mars



Low-energy (<200 eV) O+ ions

Low velocity(<10 km/s) ions dominates at altitudes <1500 km (mass-loading)

- Acceleration in central tail

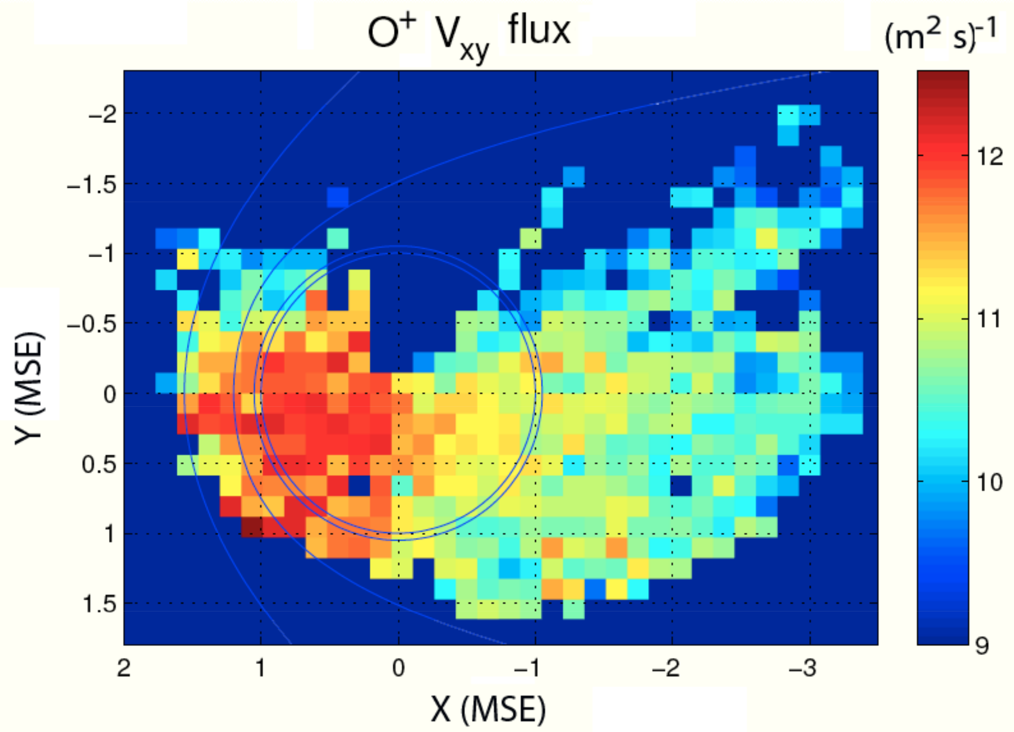


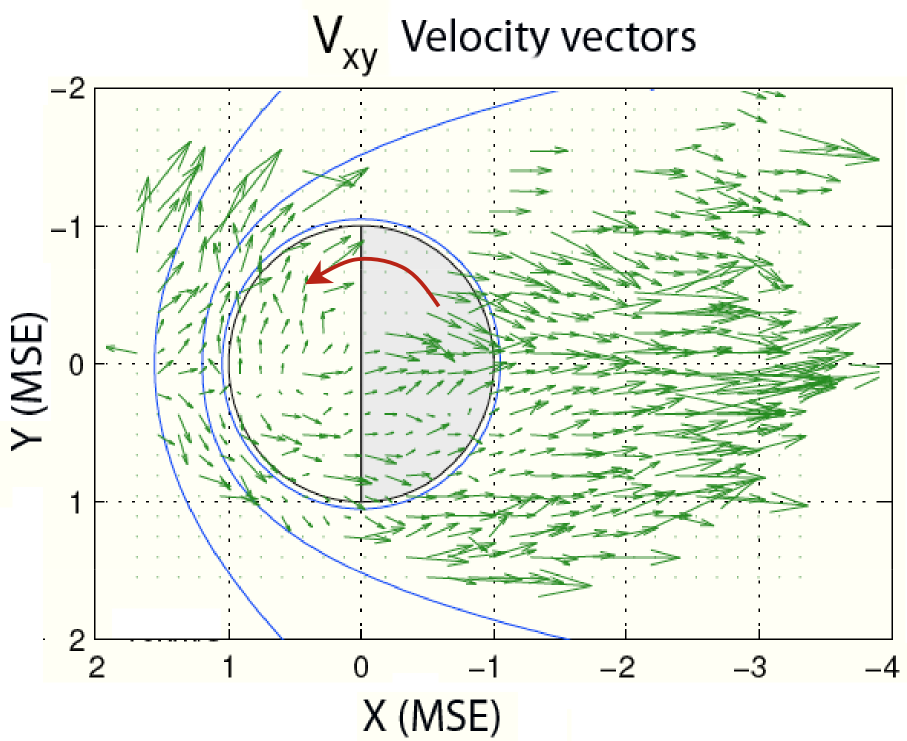
Energetic (>200 eV) O+ ions

Energetic (>30 km/s) ions generally observed at high altitudes

- keV ions in sheath (ion pickup)
- Acceleration in central tail

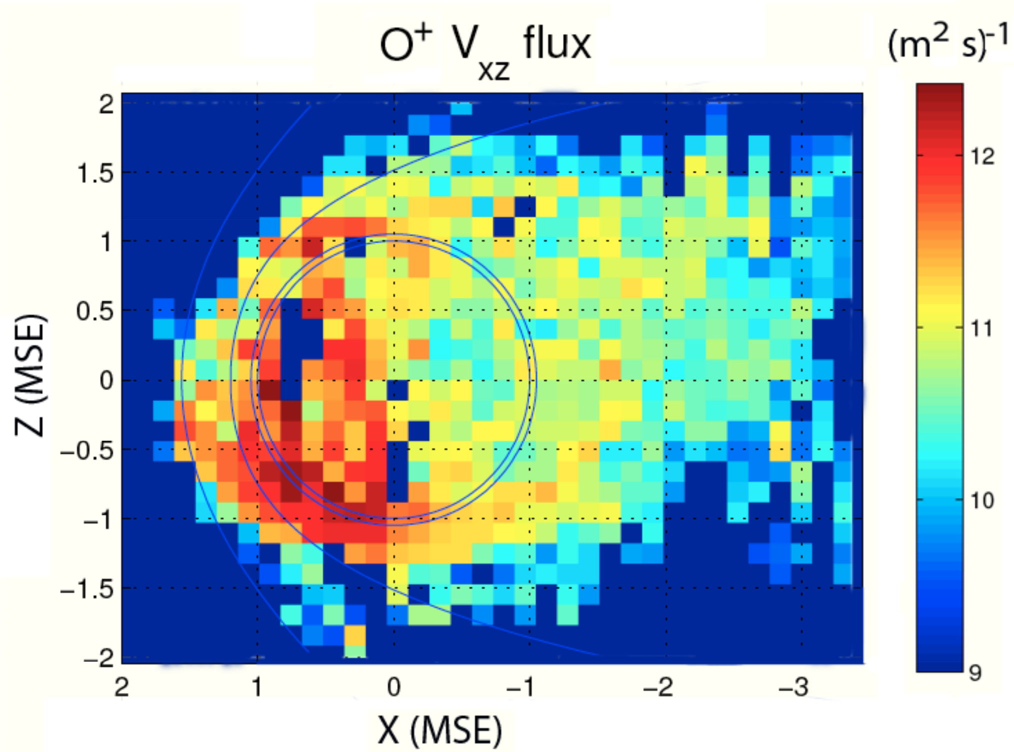
Morphology of low-energy (<300 eV) O^+ ion outflow from Mars
Dawn-dusk projection

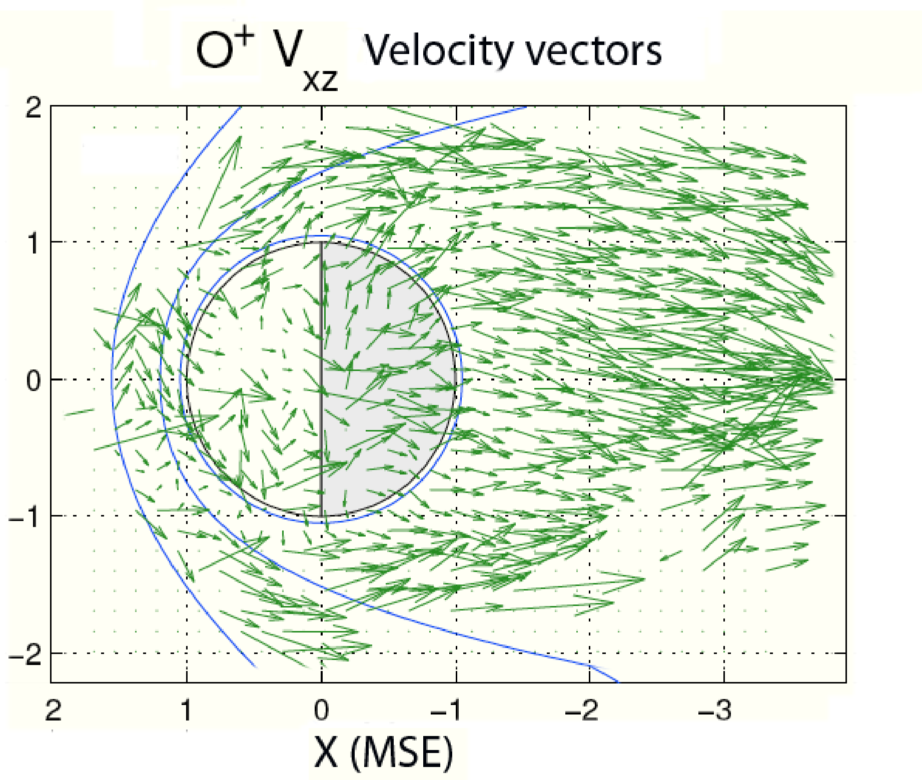




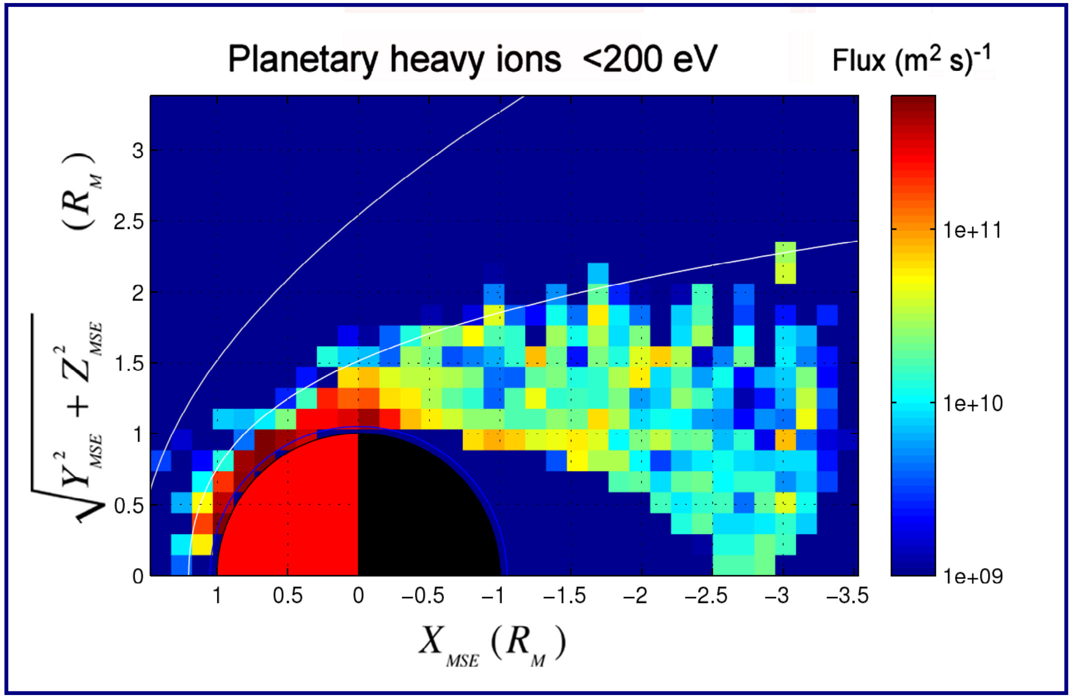
- High O^+ flux <=> low velocity (high number density) near planet
- Preference for dusk O^+ outflow (in corotation direction)
- Flux void (low O^+ flux, $<10^9$) in dawn sector (Magnus forcing, Perez-de-Tejada, 2009)
- Flow focussing towards central tail (+ energization)

Morphology of low-energy (<300 eV) O^+ ion outflow from Mars
North-south projection





- High O^+ outflow from dayside southern hemisphere (above magn. anomalies)
- Northern nightside hemisphere outflow (dayside magn. Shielding)
- High O^+ flux <=> low velocity (high number density)
- Flow focussing towards central tail (+ energization)



A comet-like escape from Mars

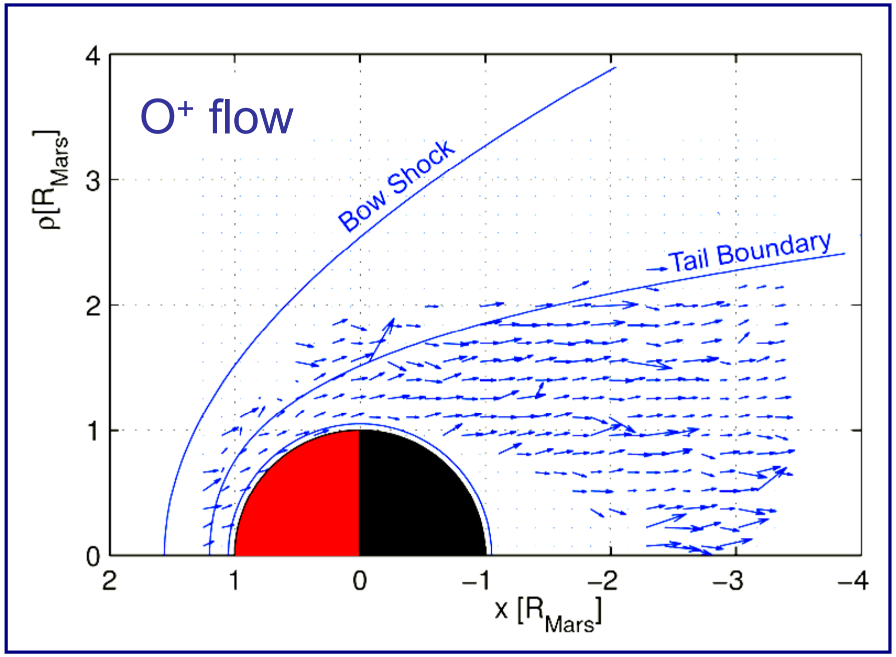
Cylindrical (X, $(Y^2+Z^2)^{1/2}$) projections

Average heavy ion (O^+, O_2^+, CO_2^+) escape rate:

$2.5 \cdot 10^{24}$ ions/s (<200 eV)

$3.3 \cdot 10^{24}$ ions/s (total)

(solar minimum values)

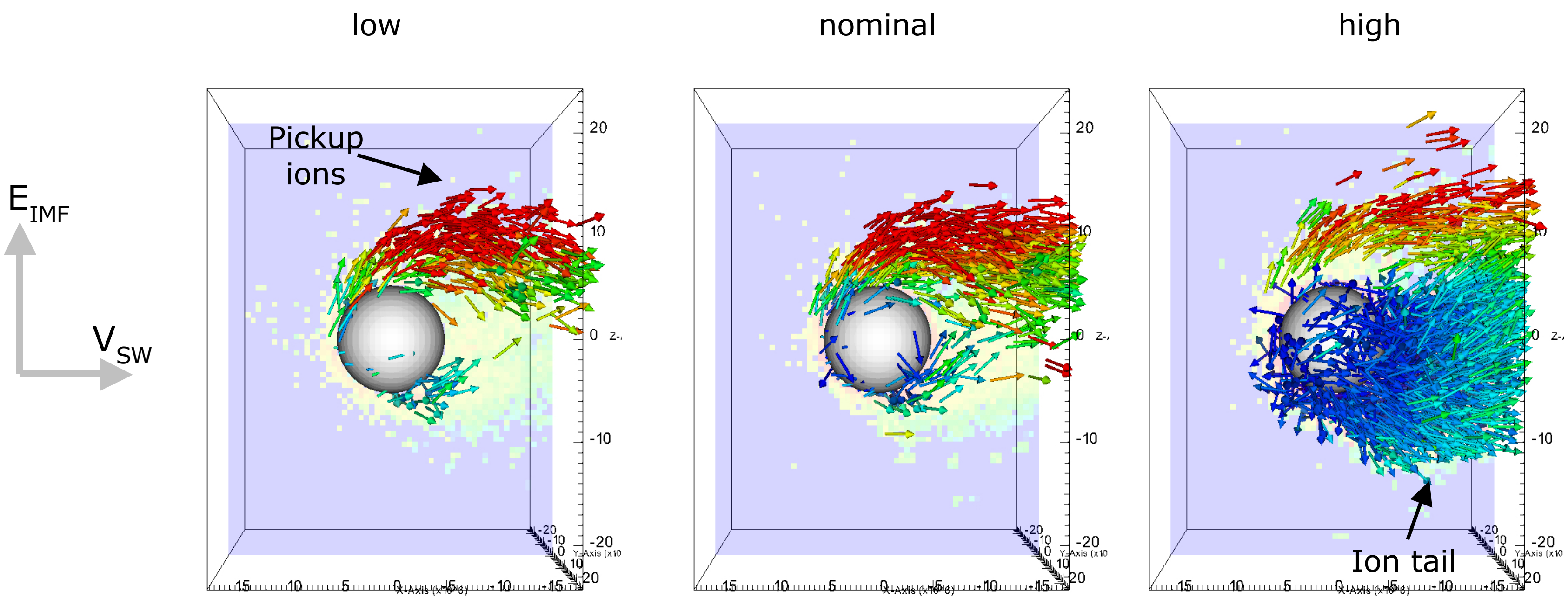


(Note: Nightside/umbra void = no data)

Low-speed (< 20 km/s) outflow of planetary ions (O^+) from the dayside and into the tail.

(Lundin et al, GRL, 2008a)

Morphology of O^+ flow - simulation (E. Kallio)

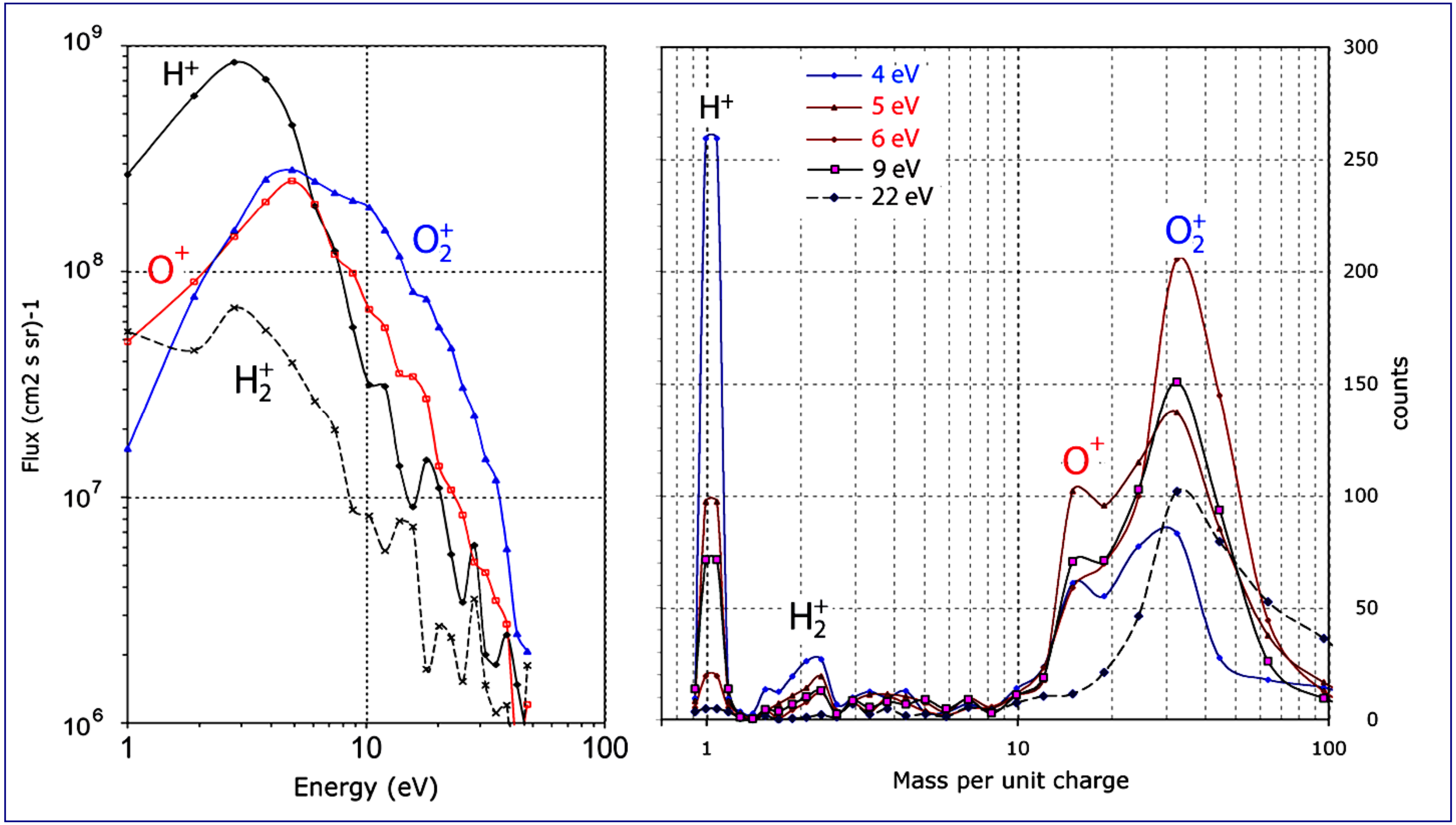


- O^+s behave as test particles.
- Escape mainly as high energy (~15 keV) pick-up ions.

(Jarvinen et al., Annales geophsicae, 2009)

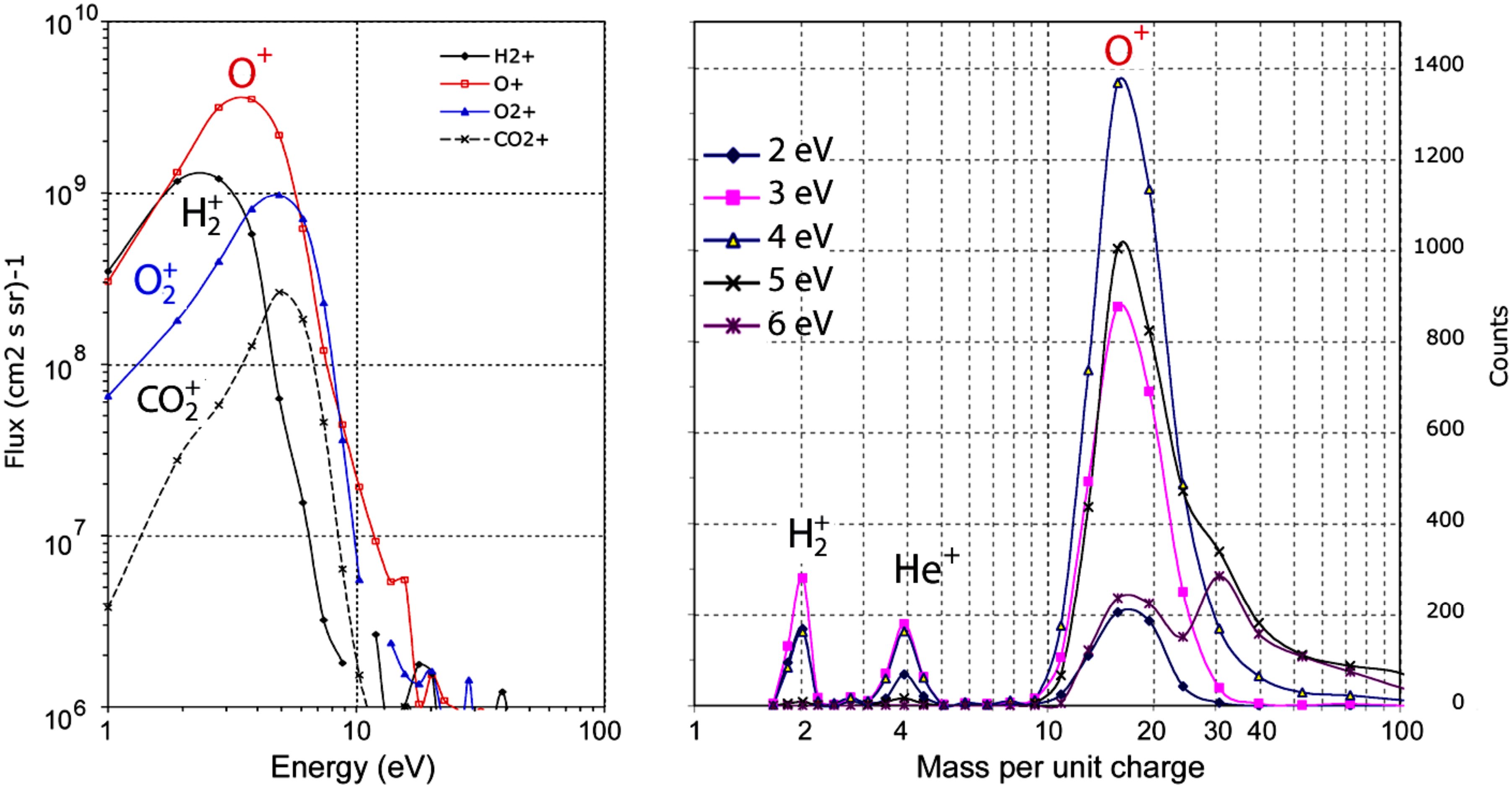
- O^+s change the magnetic configuration of the Venus' magnetosphere.
- Escape mainly through the low energy ion tail.

ASPERA3-IMA mass spectra for postacc. 7 (Oct 2008 —>)



• Ion energization mass dependent - increases with increasing mass

ASPERA3-IMA mass spectra for postacc. 4



- Low-energy H^+ "out of range", but H_2^+ is detectable
- Mass dependent ion energization
- CO_2^+ flux (m/q = 44) order of magnitude lower than O^+ flux

Average ion escape rate from Mars

Ion species	*Percentage of escape **
O^+	35%
O_2^+	22%
CO_2^+	6%
H^+	35%
H_2^+	2%

**of total escape rate: 5.5 x 10^{24} (ions/s)*

Outflow dominated by O^+, O_2^+, H^+ (92%)

Molecular ions (H_2^+, O_2^+) contributes significantly (30%) to the ion escape

CO_2^+ contributes to about 6% of the ion escape => Minute carbon escape

Cold ionospheric ion outflow, including Hydrogen

	$\Phi(O^+)$	$\Phi(O_2^+)$	$\Phi(O,O_2)$	$\Phi(H^+)$	$\Phi(H,H_2)$	$\Phi H/\Phi O$ Aver.	$\Phi H/\Phi O$ Simult.
Average flux ($m^{-2}\ s^{-1}$)	$5.0 \cdot 10^{10}$	$3.3 \cdot 10^{10}$	$8.4 \cdot 10^{10}$	$5.1 \cdot 10^{10}$	$5.4 \cdot 10^{10}$	**0.64**	**1.3**
Escape rate* (part/s)	$2.0 \cdot 10^{24}$	$1.3 \cdot 10^{24}$	**$3.3 \cdot 10^{24}$**	$2.0 \cdot 10^{24}$	**$2.1 \cdot 10^{24}$**		

*Computed based on symmetric ion escape through an area $=4.0 \cdot 10^{13}\ m^2$ ($r = 1{,}15\ R_{Mars}$)

H/O ion outflow ratio ≈1

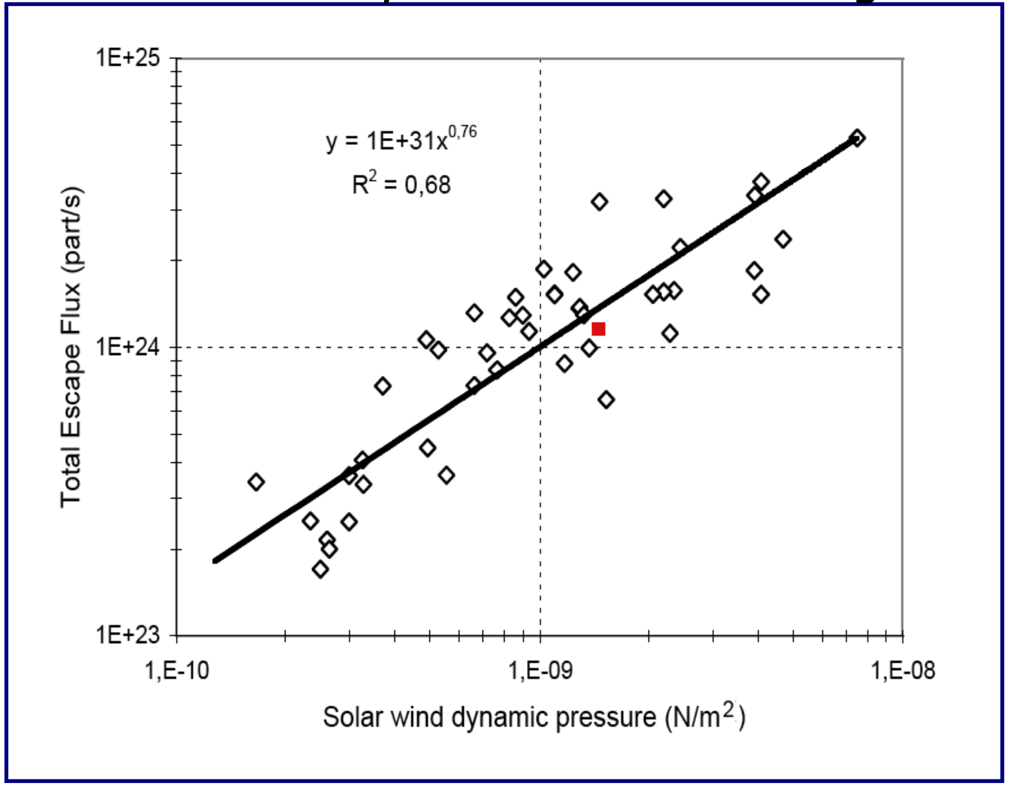
⇒ Water the ultimate source for ≈90% of the ion escape from Mars

⇒ Water is the volatile constituent most prone to escape from Mars

(Lundin et al, GRL, 2009)

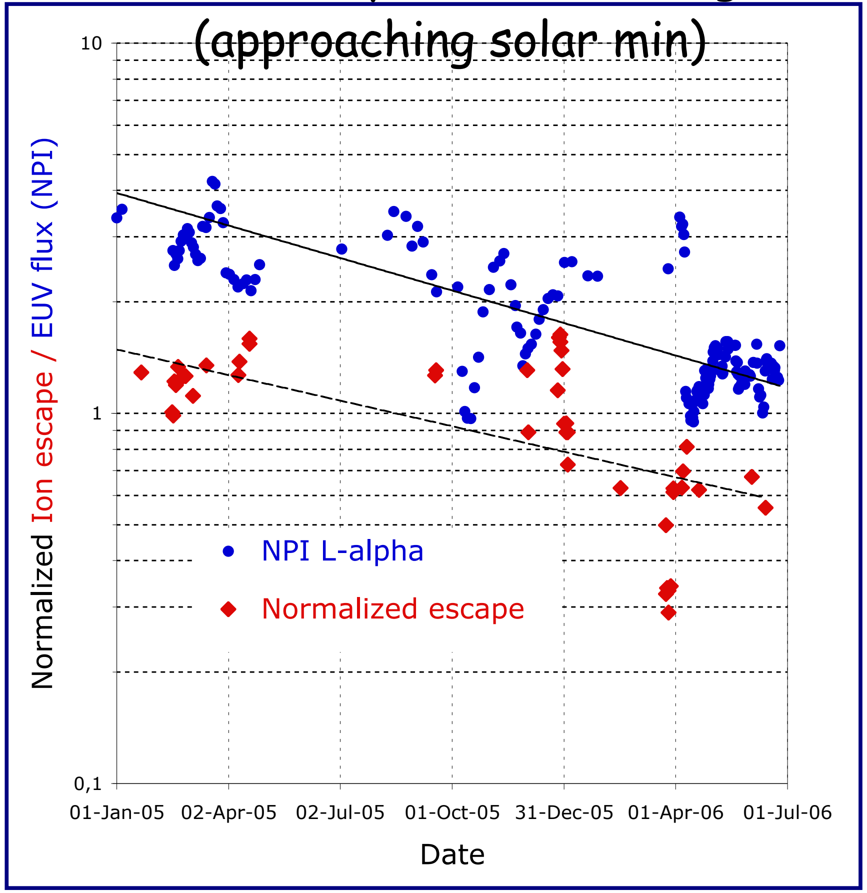
Mars ion escape - Solar wind and solar EUV dependence

Variability of solar wind forcing



Positive correlation between solar wind dynamic pressure and ion escape - Escape stimulated by enhanced solar wind forcing (increased pressure => waves into the ionosphere)

Variability of EUV forcing (approaching solar min)



Exponential escape decrease by ≈2.5 from Jan 2005 to July 2006 (NPI/EUV-background decrease ≈2.7)

(Lundin et al, GRL, 2008a)

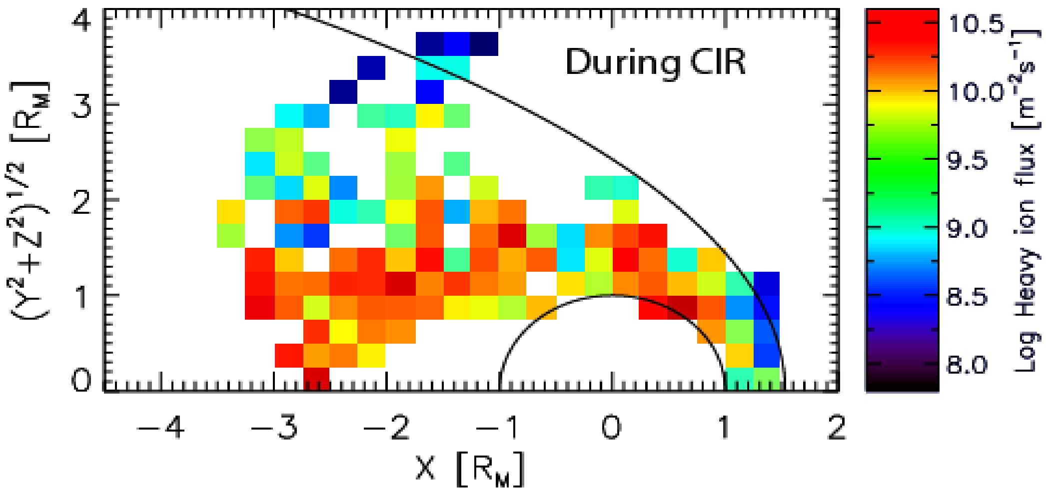
Atmospheric escape during CIR

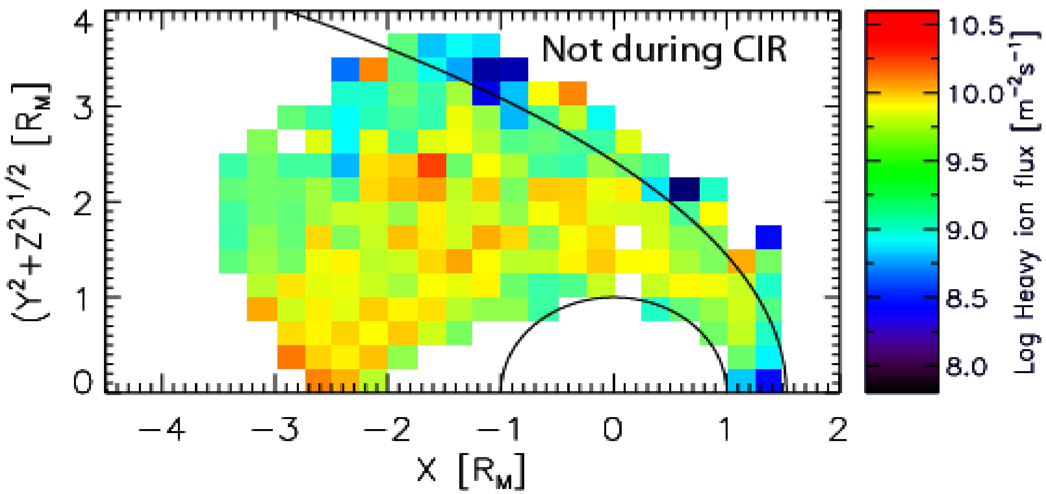
- The amount of outflowing heavy planetary ions increases by a factor of ~2.5 when a CIR passes by

- ~30% of the total outflow of heavy planetary ions takes place during ~15% of the time.

- Important implications for atmospheric evolution at Mars.

Edberg et al., (GRL, 2010)



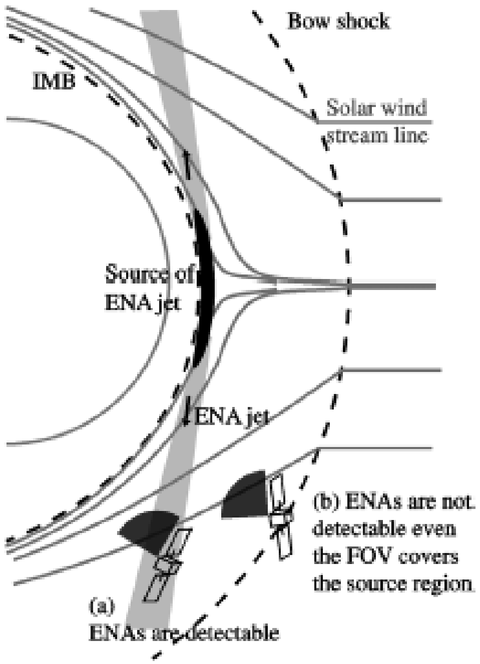


Exosphere, ENA, X-ray

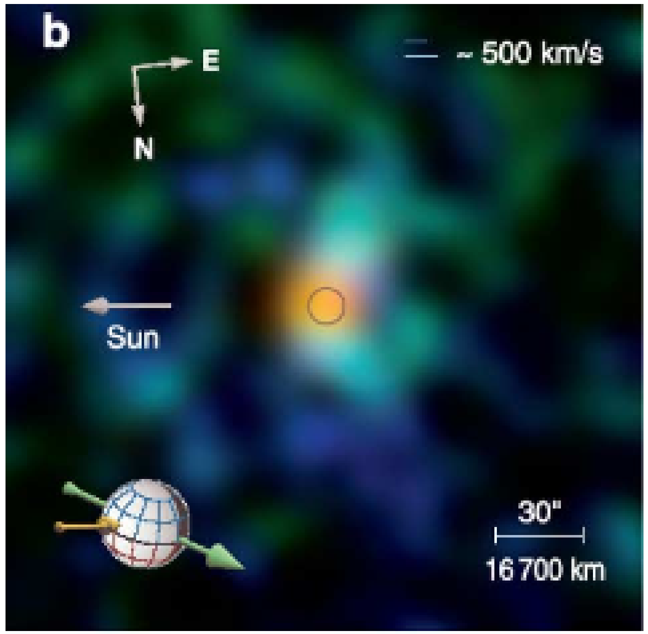
Exosphere - extension into space and escape

- *Sputtering, Photochemical escape (Chaufray et al, 2007, Fox and Hac, 2009)*
- *ENA measurements, implications for escape?*

X-ray and ENAs, Simulations



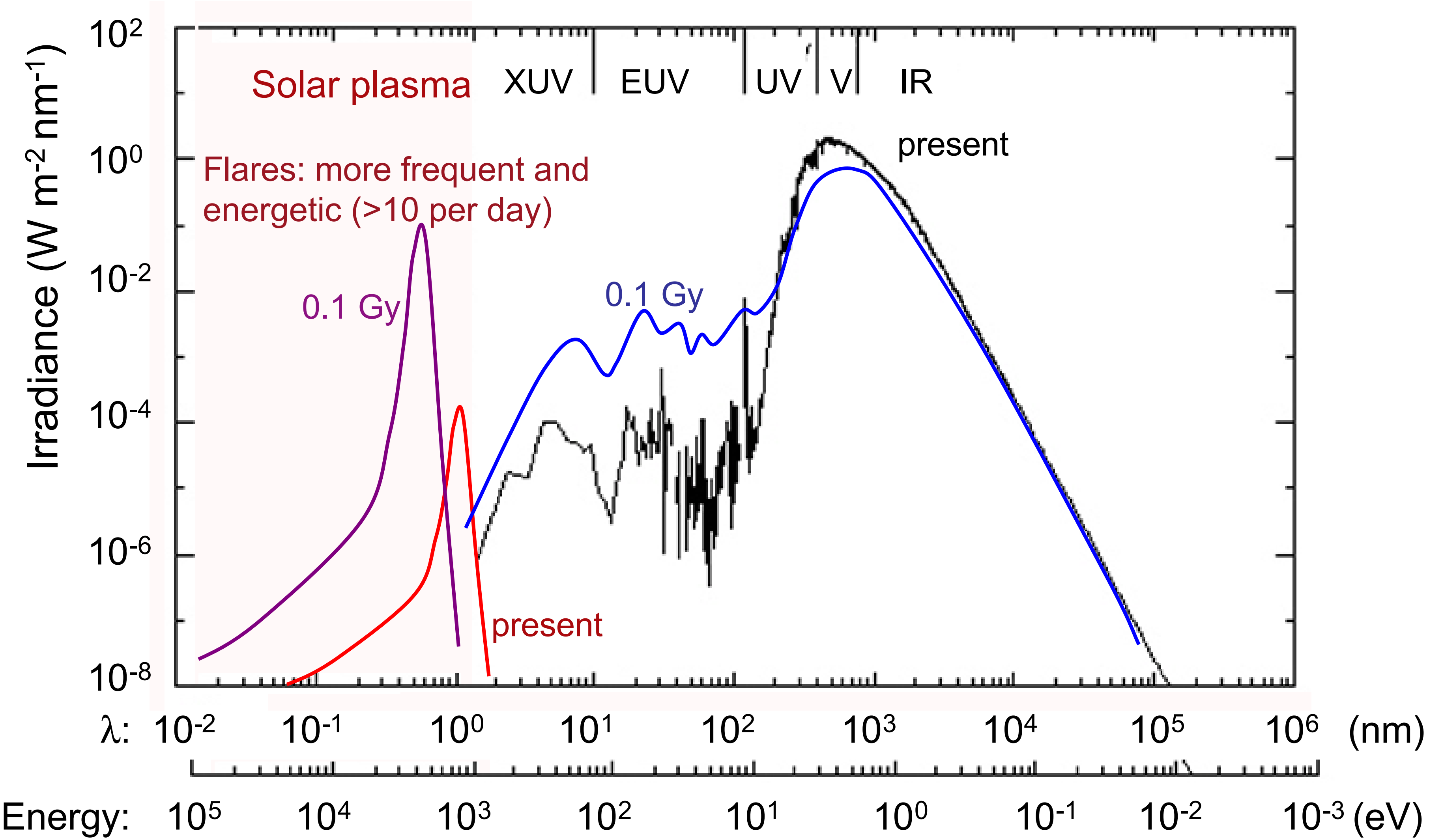
(Futaana et al., 2006)



(Dennerl et al., 2006)

(Perez-de-Tejada et al., 2009)

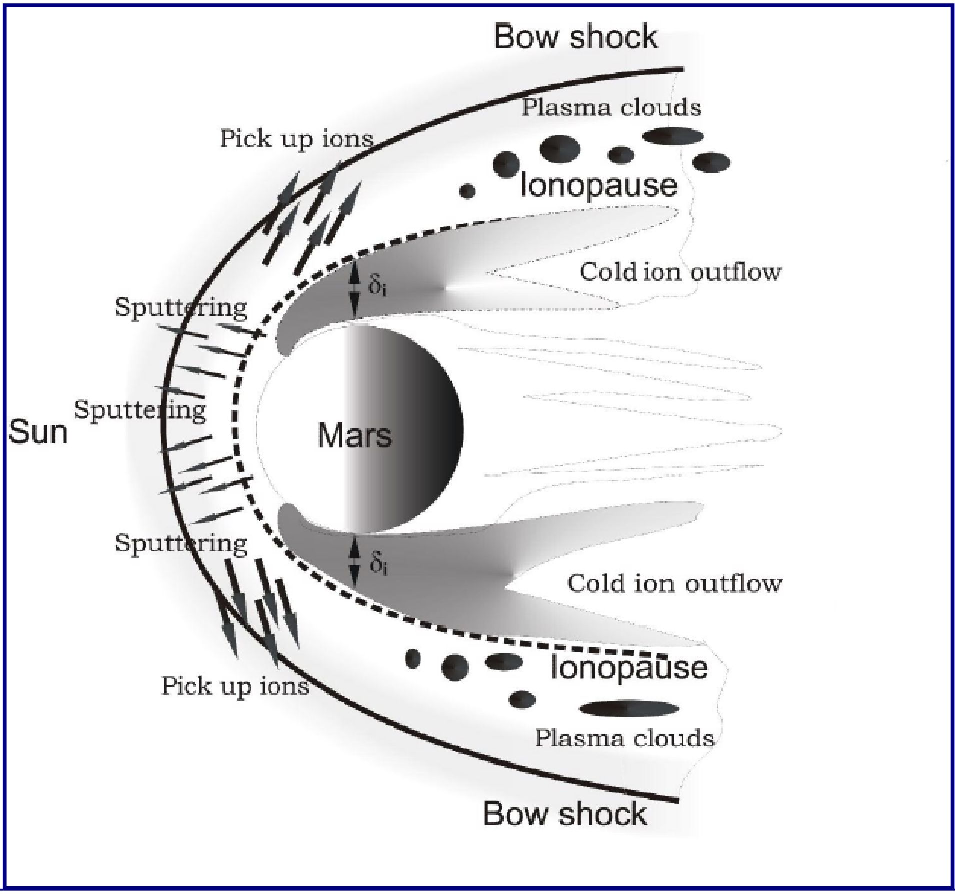
4. Solar impact on the atmospheric evolution (0.1 - 4.5 Gy)

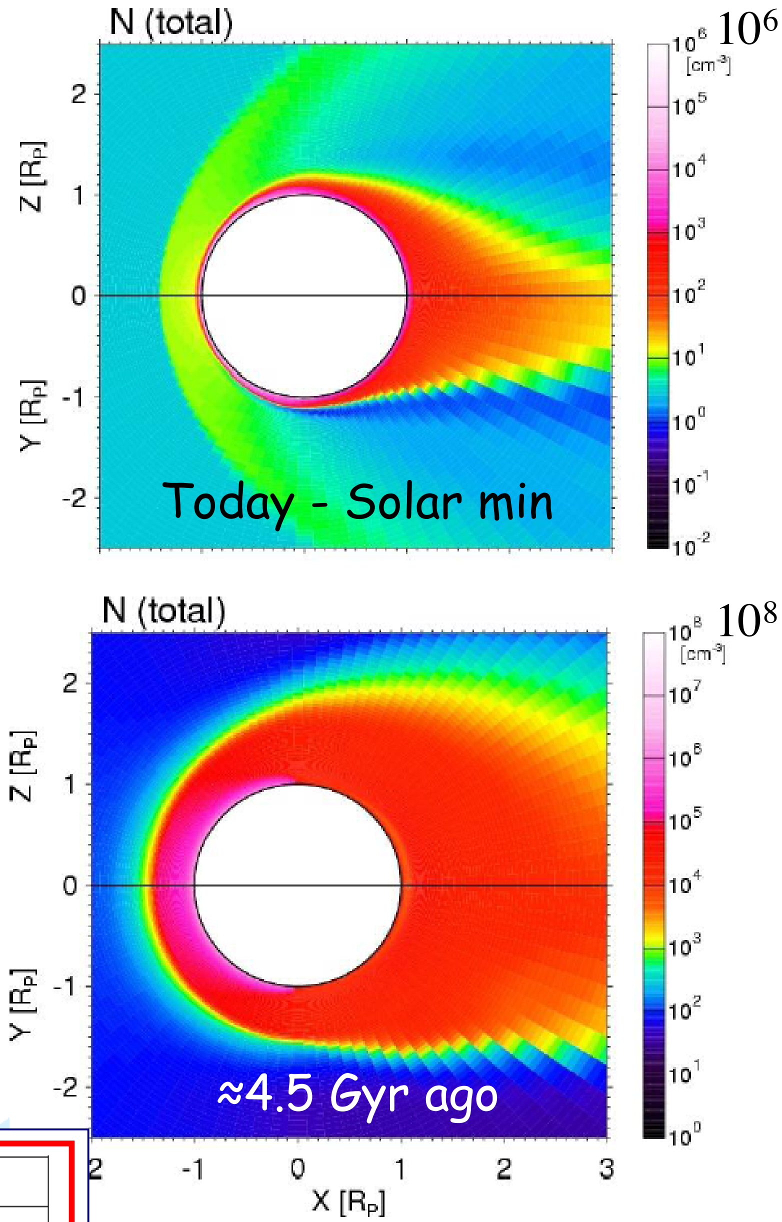


(Adapted from Wood et al, 2002, 2004, and Ribas et al, 2005)

Atmosphere and water escape from Mars

Simulations, 0.1 - 4.5 Gyr (Terada et al. 2008)





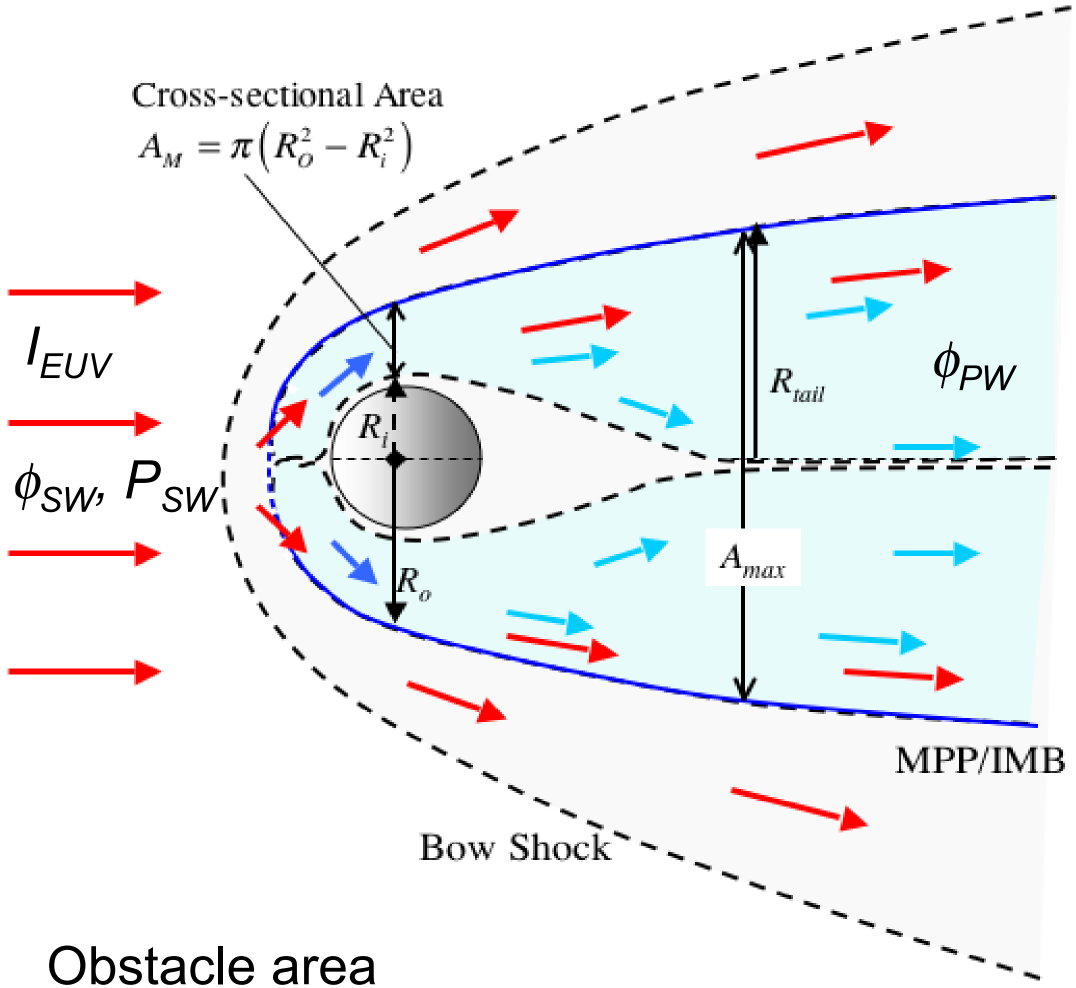
Ion pickup loss ~ 4.45 – 4.6 Gyr ago	Cold ion outflow ~ 4.45 – 4.6 Gyr ago
O^+: ~ 1.5×10^{28} s^{-1}	O^+: $1.8 \times 10^{28} - 1.2 \times 10^{29}$ s^{-1}
O_2^+: ~ 5×10^{25} s^{-1}	
CO_2^+: ~ 3×10^{25} s^{-1}	

=> 10 - 70 m loss of water

Semi-empiric model of the solar forcing of Mars

Solar EUV, X-ray (XUV)
Atmosphere heating, ionization & expansion +thermal escape

Solar wind (n, v, E)
Ionospheric plasma escape + obstacle size



$A_M = A(I_{EUV}, P_{SW})$	Obstacle area
ϕ_{SW}	Solar wind
ϕ_{PW}	Planetary wind (ionospheric plasma)

Plasma escape model

Solar wind momentum flux :
(Wood et al., 2002):

$$\Phi_S(t) \approx \Phi_{S0} \cdot t^{-\alpha} \qquad \alpha \approx 1.8$$

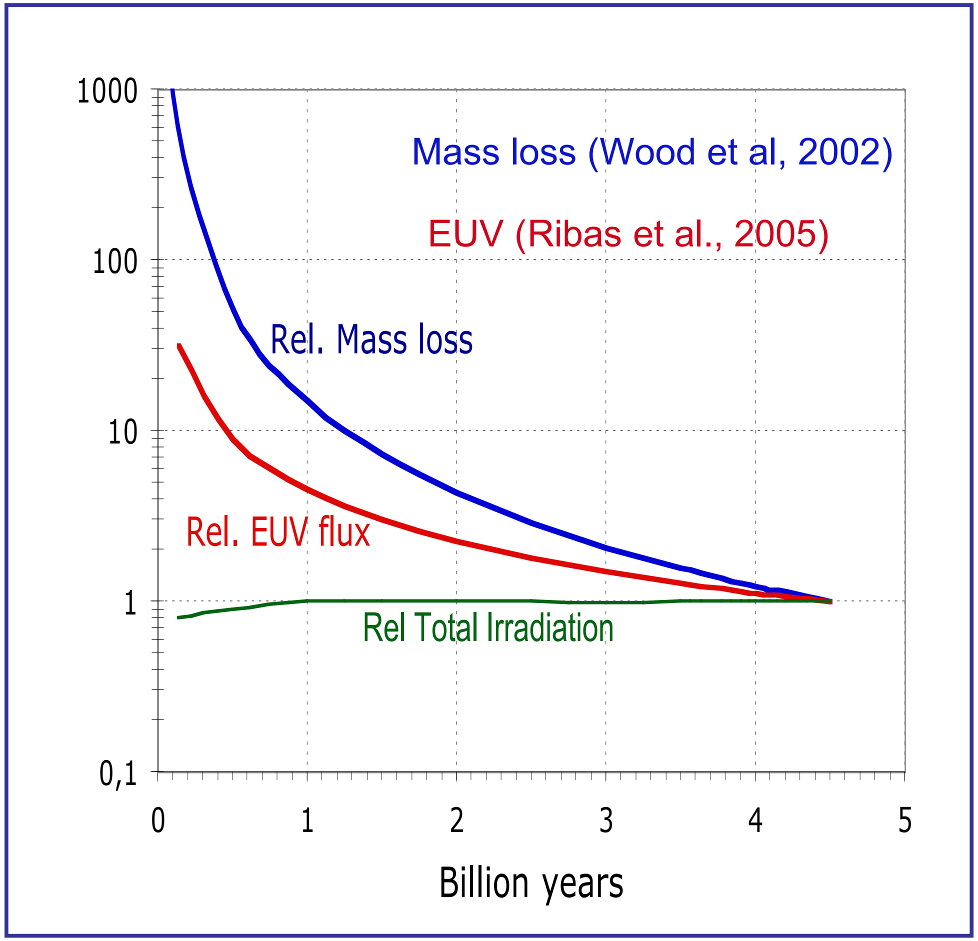
Solar wind momentum flux proportional to Planetary wind momentum flux (Perez-de-Tejada, 1987):

$$\Phi_S(t) \propto \Phi_M(t) \approx \Phi_{M0} \cdot t^{-\alpha}$$

Solar EUV flux : (Ribas et al., 2005).

=> Obstacle increases with solar EUV flux, atmospheric density and temperature, assume:

$$A_{EUV}(t) = A_{M0} \cdot t^{-1.2}$$



Very conservative! A solar EUV flux increase by a factor of 3 enhances outflow rates by a factor of 100 from the Earth (Cully et al. 2003)

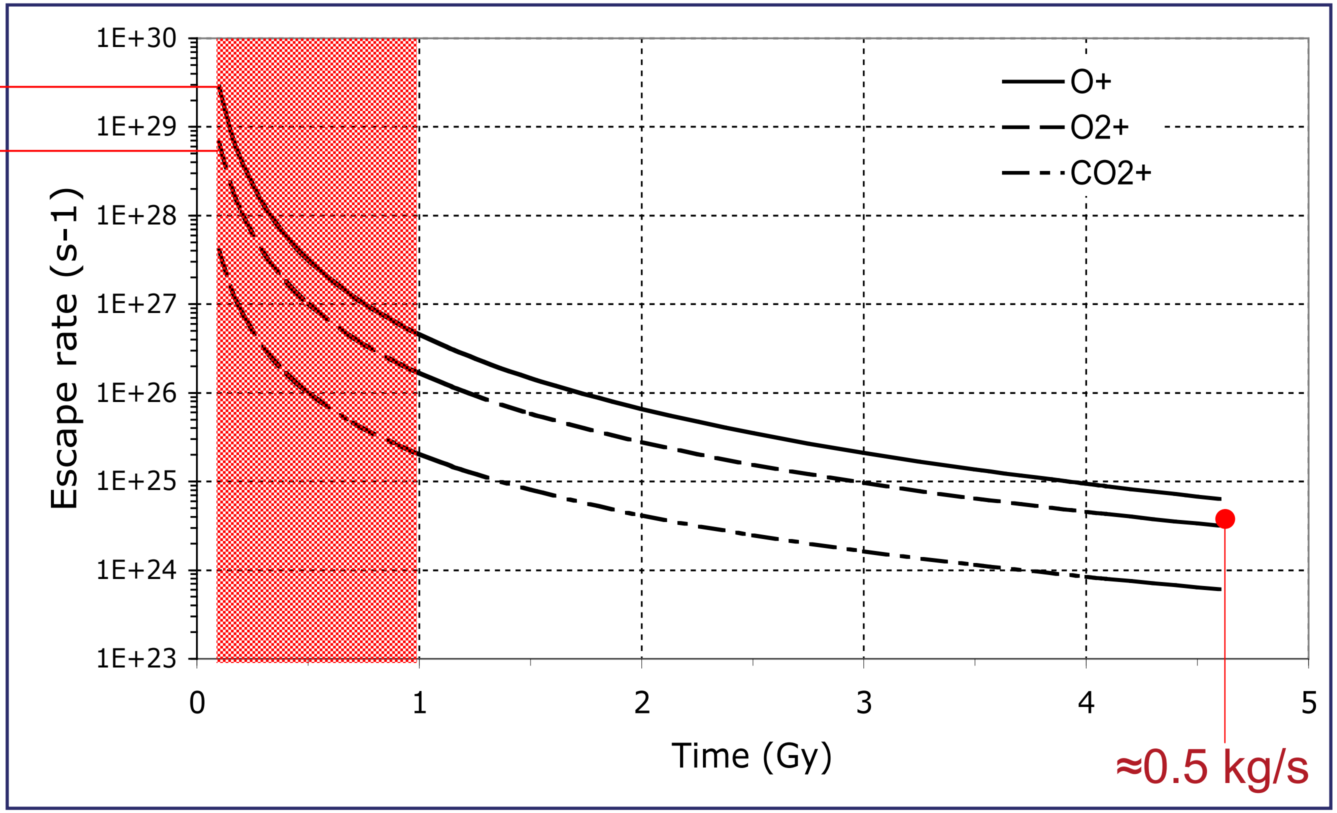
Long-term escape from Mars

Scaling escape fluxes backward in time using:

1. present escape values (averaged over a solar cycle)
2. the solar EUV and solar wind evolution (0.1 - 4.6 Gy) (Wood et al, 2002, 2005 and Ribas et al., 2005)

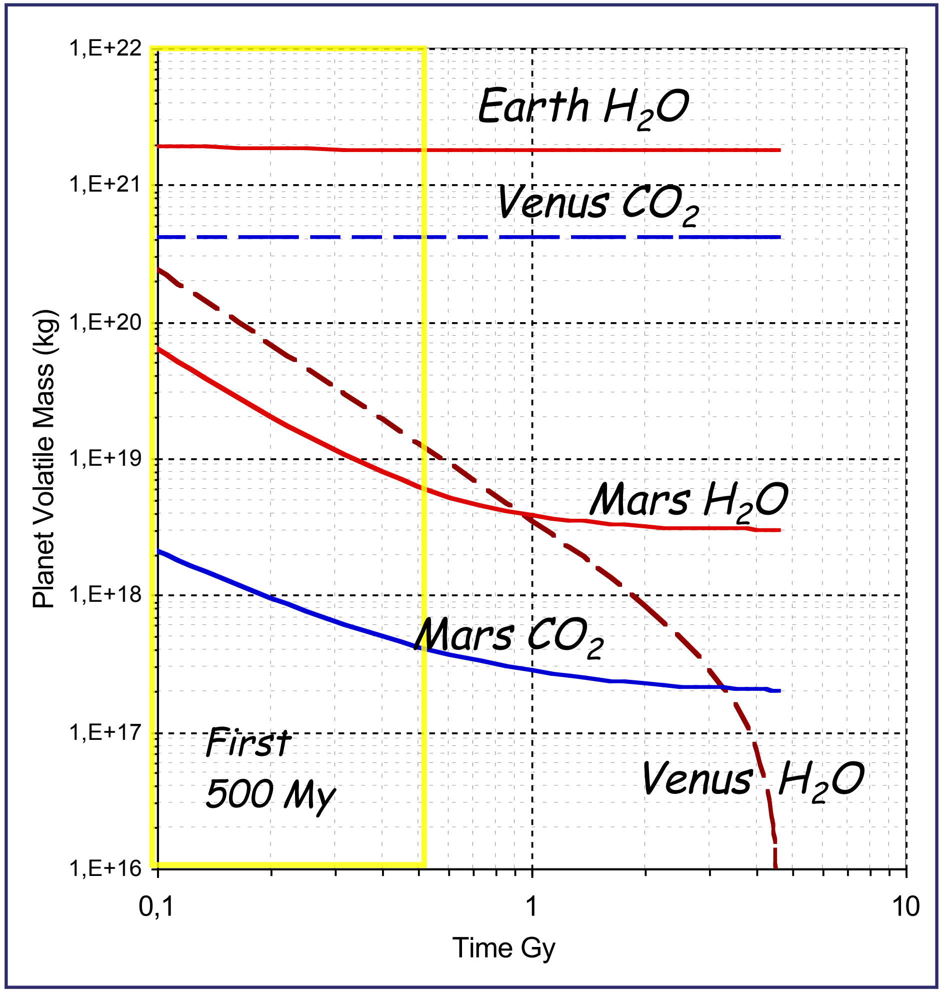
O^+ $2.9 \cdot 10^{29}$ s^{-1}

O_2^+ $6.7 \cdot 10^{28}$ s^{-1}



Note O^+ escape rate close to Terada max rate $1.2 \cdot 10^{29}$ s^{-1}

Long-term loss of volatiles from the Earth-like planets



Total mass escaping from t_0 to t_1:

$$S_{Mt_1} = \int_{t_0}^{t_1} A_M(t) \cdot \Phi_M(t)\, dt \qquad (kg)$$

Based on present average escape rates from Earth (≈1 kg/s), Mars (≈0,5 kg/s) and Venus (≈1 kg/s).

- *Earth - permanent magnetic shield*
- *Venus and Mars - no magnetic shield*

- *Major mass loss for Mars and Venus during the first ≈500 My*
- *Venus lost "all" water because of amplified greenhouse conditions (CO_2)*

Hydrogen escape determined from Lyman alpha (Anderson, 1974) is a factor of 30-40 higher than our measured H^+ escape rates + dissociated recombination (Fox, 2009) suggests an order of magnitude higher O and H escape rates

CONCLUSIONS 1

- Solar forcing, by solar XUV/EUV radiation and the solar wind, leads to planetary thermal and non-thermal atmospheric and ionospheric escape.
- Outflowing planetary ions today originates primarily from atmospheric water (minute carbon escape) - from an arid planet with an atmosphere dominated by CO_2
- Despite low water mixing ratios (h) in the atmosphere the present loss of water from Mars (with h =10^{-3}- 10^{-5}) is similar to, or higher, than that from the magnetically shielded Earth (with h ≈10^{-2})
- Simulations and modelling based on measured ion escape suggests that enhanced forcing from the early Sun resulted in a loss of water from Mars corresponding to 10-70 m GEC.
- Considering also hydrogen escape (Anderson, 1974) and dissociative recombination (Fox and Hac, 2009) the loss may have corresponded to **≈1000 m GEC**!
- Narrows the time for emerging life on Mars to the first ≈1 Gy