Ion and neutral gas escape from the terrestrial planets

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	H	O	O_2
Earth	0.6	9.7	19.4
Venus	0.5	8.2	16.4
Mars	0.13	1.8	3.6

Process

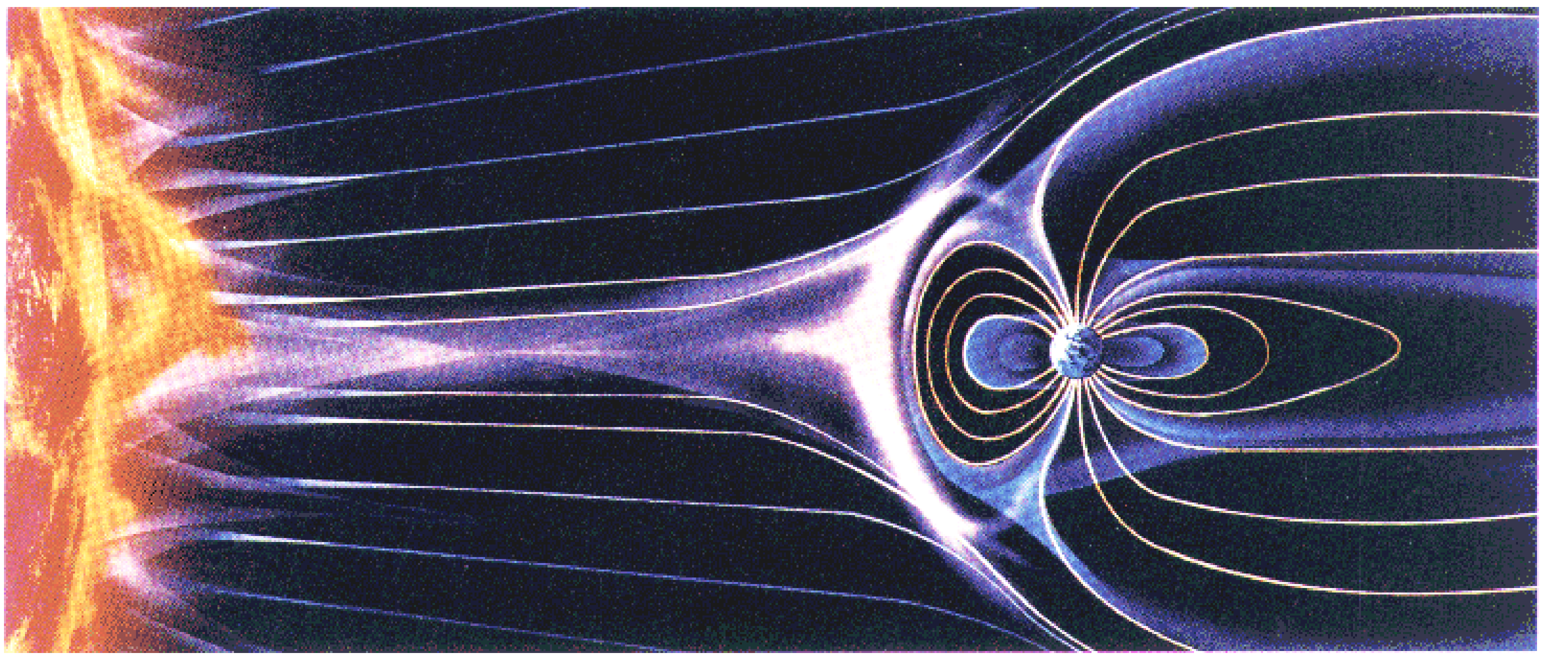
ee energy

Magnetic field energy

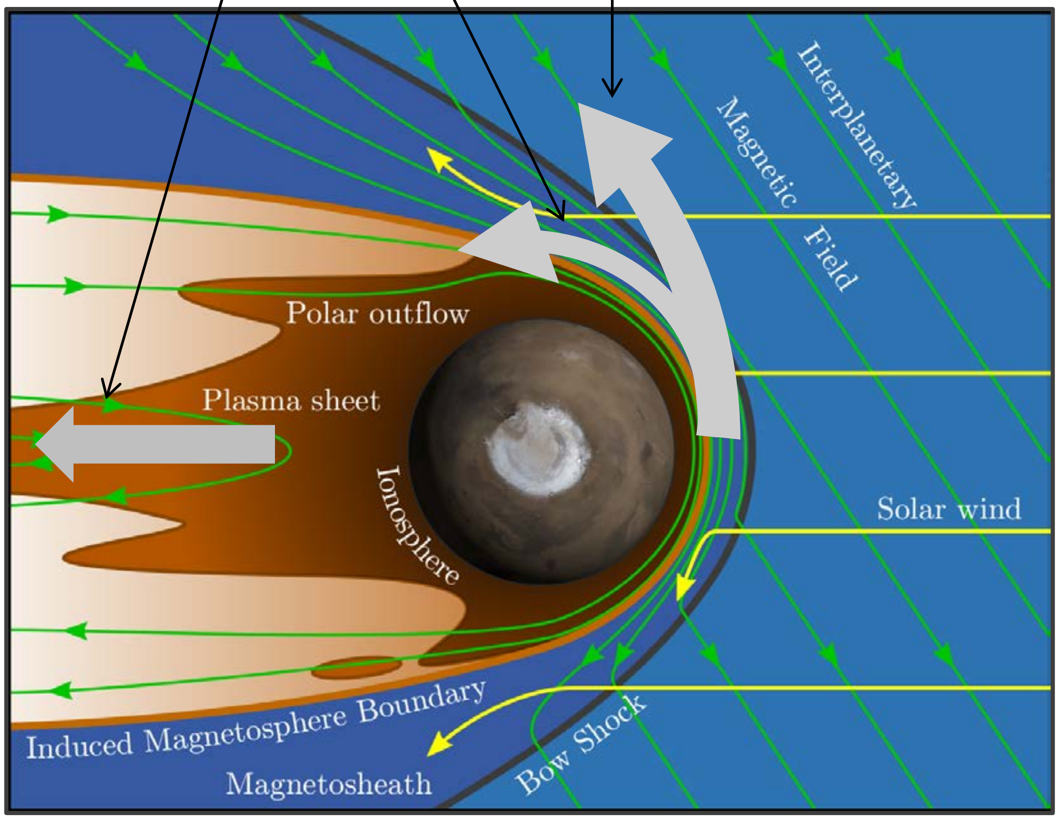
What is the role of the intrinsic magnetic field?

The current thought pattern (paradigm)

The present paradigm: **a magnetosphere created by an intrinsic magnetic fields protects the planetary atmosphere from the erosion resulted from the solar wind**. The magnetospheric fields separate the moving interplanetary magnetic field "frozen-in" in the solar wind and the upper ionized part of the atmosphere, ionosphere. The ionospheric ions are not subjected to the induced and convective electric fields and cannot be accelerated to energies above the escape energy and leave the planet. Contrary, atmospheres of non-magnetized Mars and Venus are subject to the erosion because the interplanetary magnetic field can reach their ionospheres.



$$E = E_{ps} + E_{pw} + E_{conv} = \frac{J \times B}{n_e e} - \frac{\nabla P_e}{n_e e} - V \times B$$

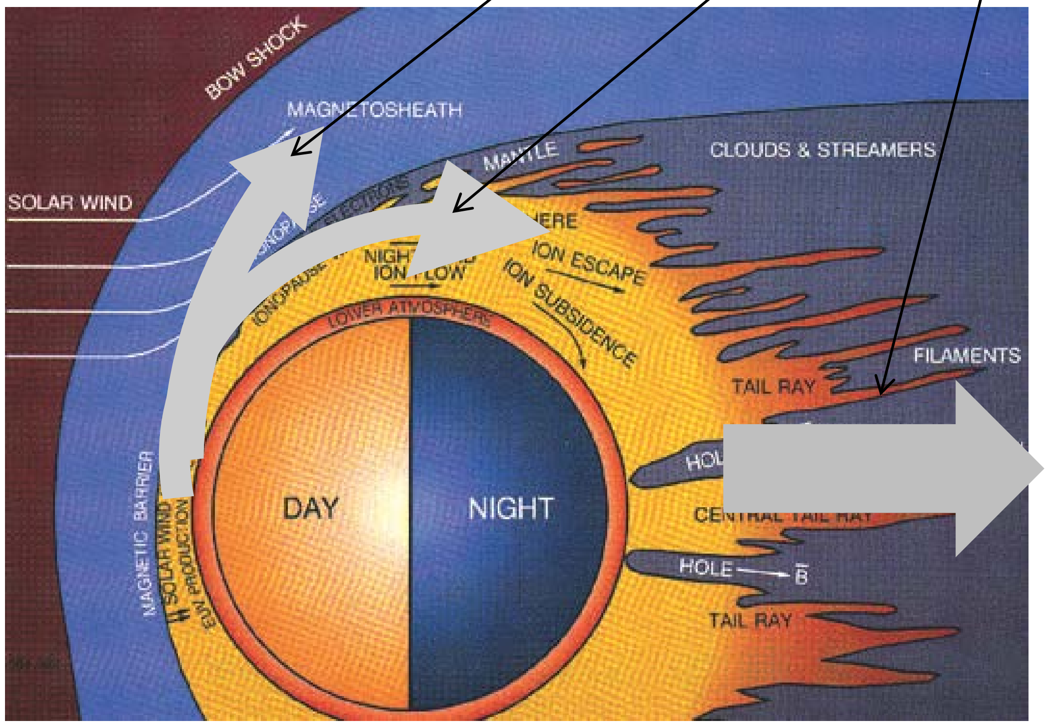


$$Q = (2.7 \pm 0.4) \cdot 10^{24}\ s^{-1}$$

(10 years average)

Ramstad et al., 2015

$$E = E_{conv} + E_{pw} + E_{ps} = -V \times B - \frac{\nabla P_e}{n_e e} + \frac{J \times B}{n_e e}$$

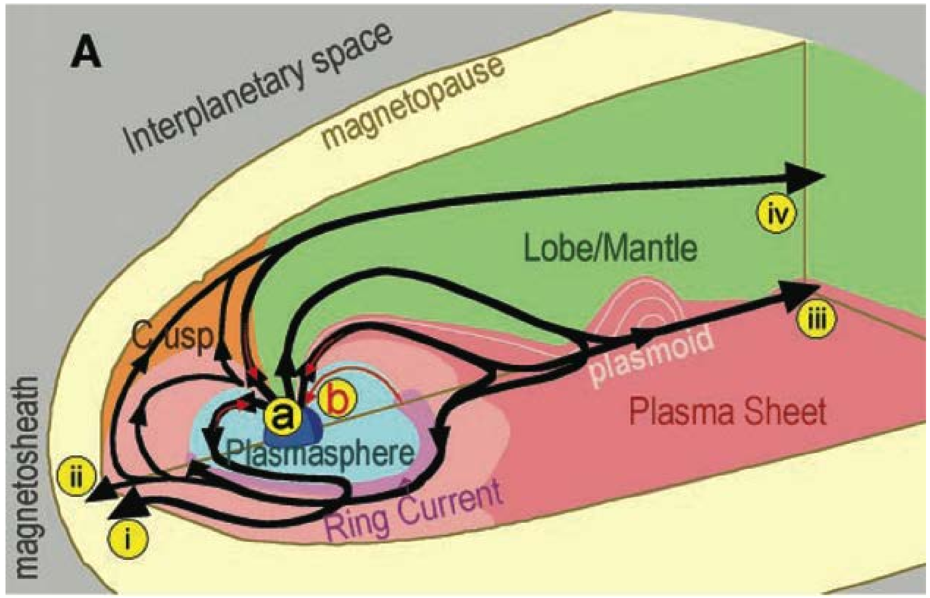


$$Q = (4.7 \pm 0.4) \cdot 10^{24}\ s^{-1}$$

(solar minimum)

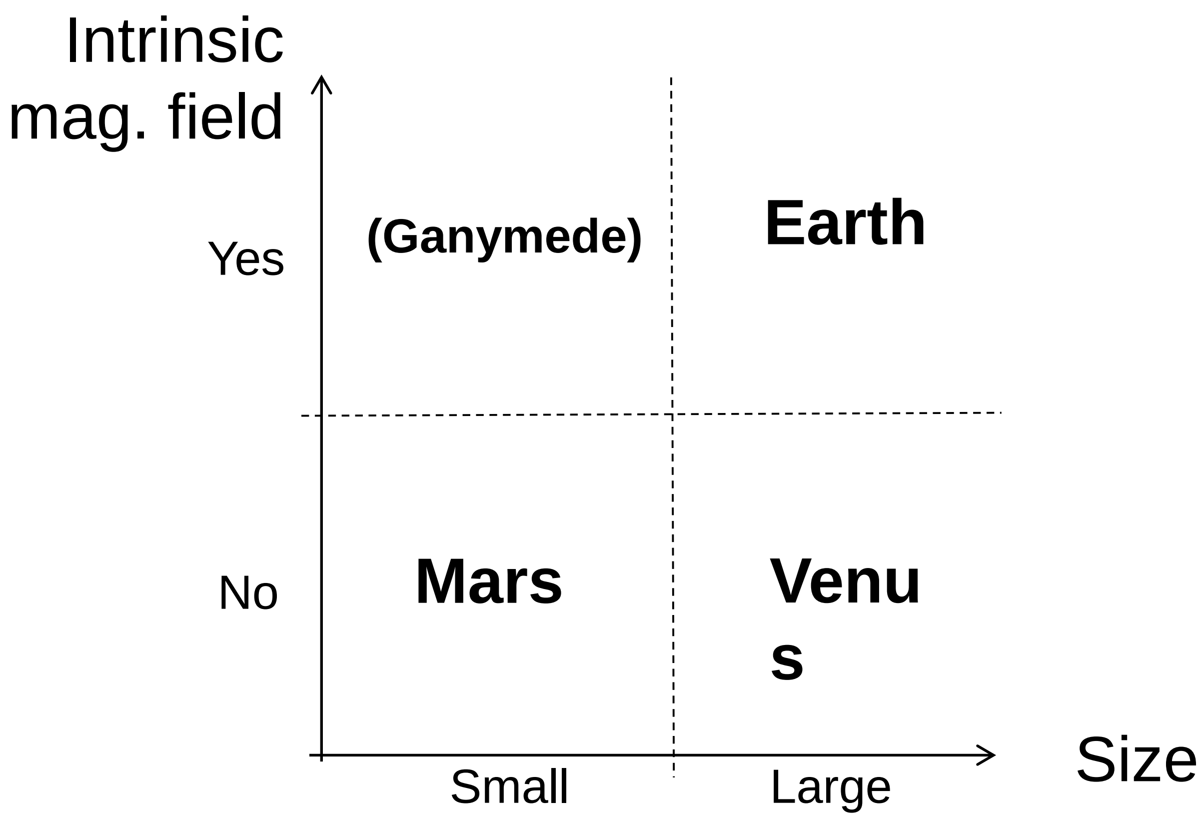
Nordström et al., 2012

- Escape at the Earth through the polar region is 2 times higher than the total escape: 2 / 3 return to the ionosphere (*Seki's et al., 2001).*



Escape rate, 1/s	Reference	Comment
$20 \cdot 10^{24}$	*Nilsson et al., 2009*	Cluster, solar maximum, limited coverage, only outflow through cusp
$45 \cdot 10^{24}$	*Arvelius et al., 1989*	Cluster, solar maximum, through 5Re sphere
$5 \cdot 10^{24}$	*Seki et al., 2001*	Geotail, solar minimum, limited coverage, gross balance (outflow – inflow)

Why are the ion escape rates about the same or even higher from the Earth?



The ion escape rate is determined by the total energy transferred from the solar wind into the ionosphere and is thus limited by the transfer efficiency and the size of the interaction region.

The intrinsic magnetic field does not protect planetary atmospheres

Transfer (coupling) function

$$k = \frac{P}{(A\,\rho V^3)}$$

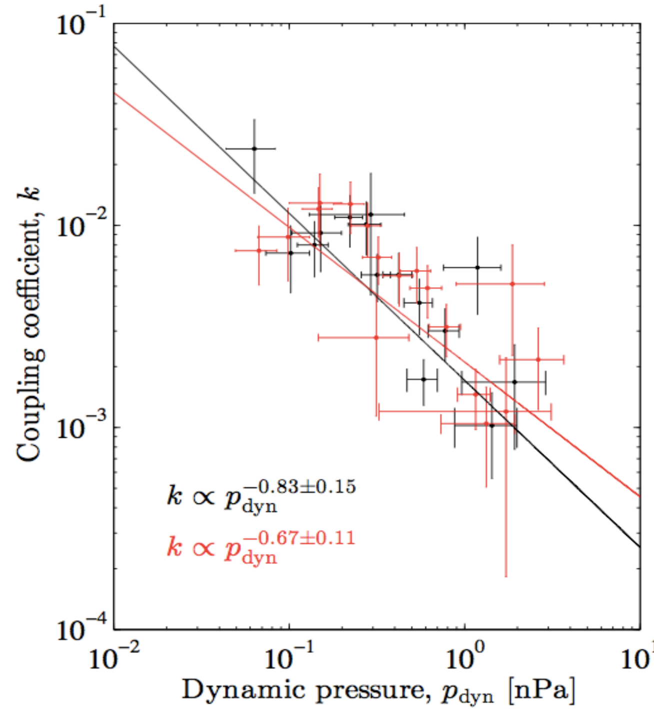
P Total escape power (~Q·E)

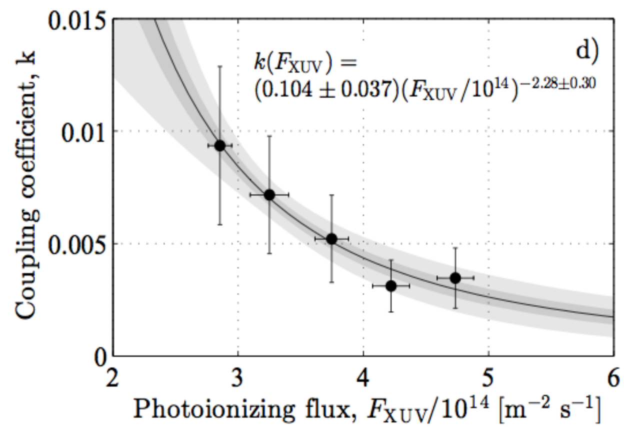
A interaction area

V solar wind velocity

ρ solar wind density

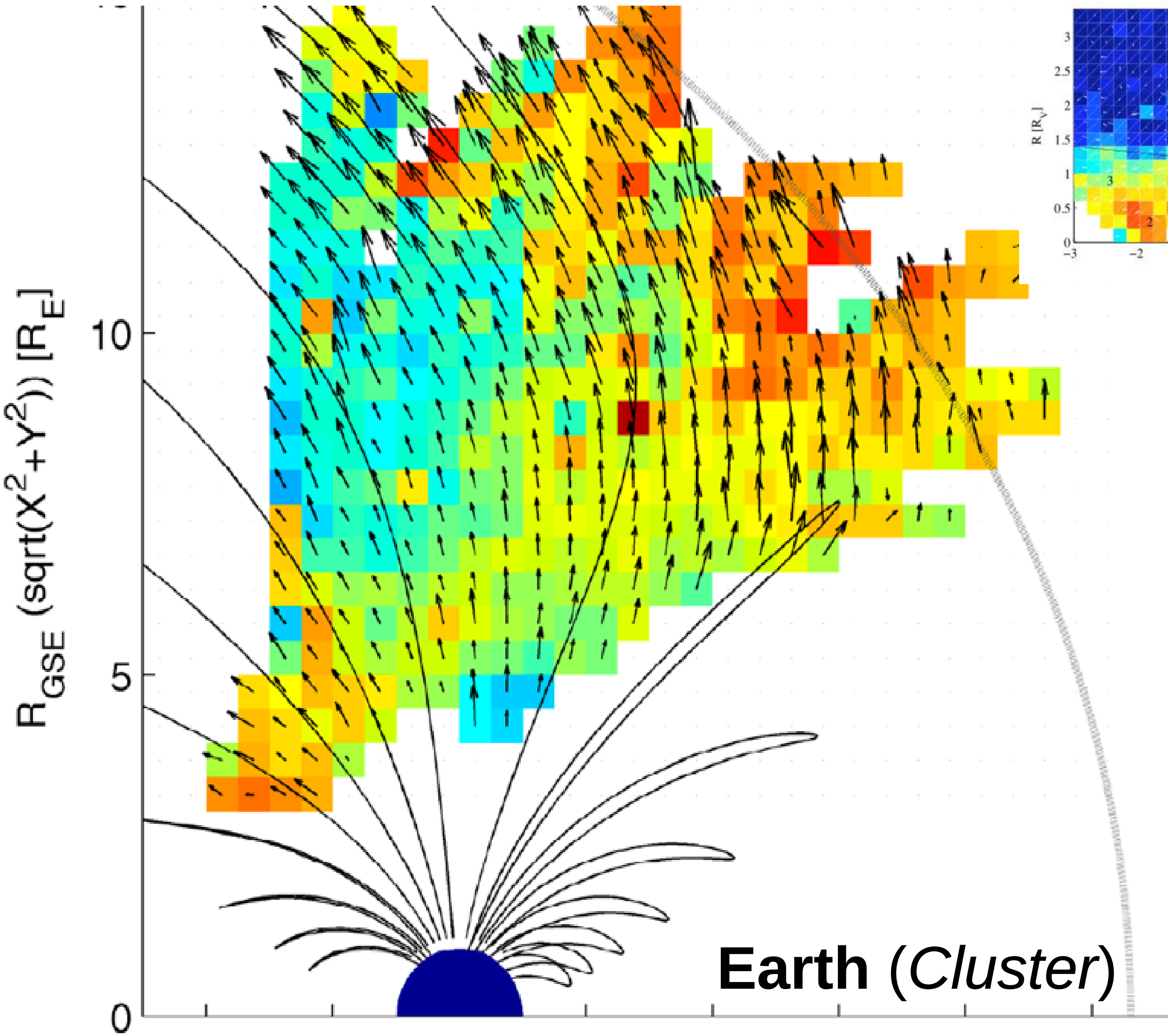
$$Q = k\;A\,(\frac{\rho V^3}{E})$$

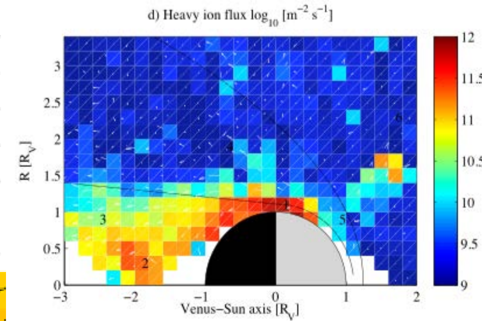




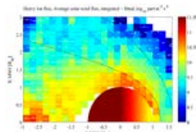
Ramstad et al., 2017

Size does matter!





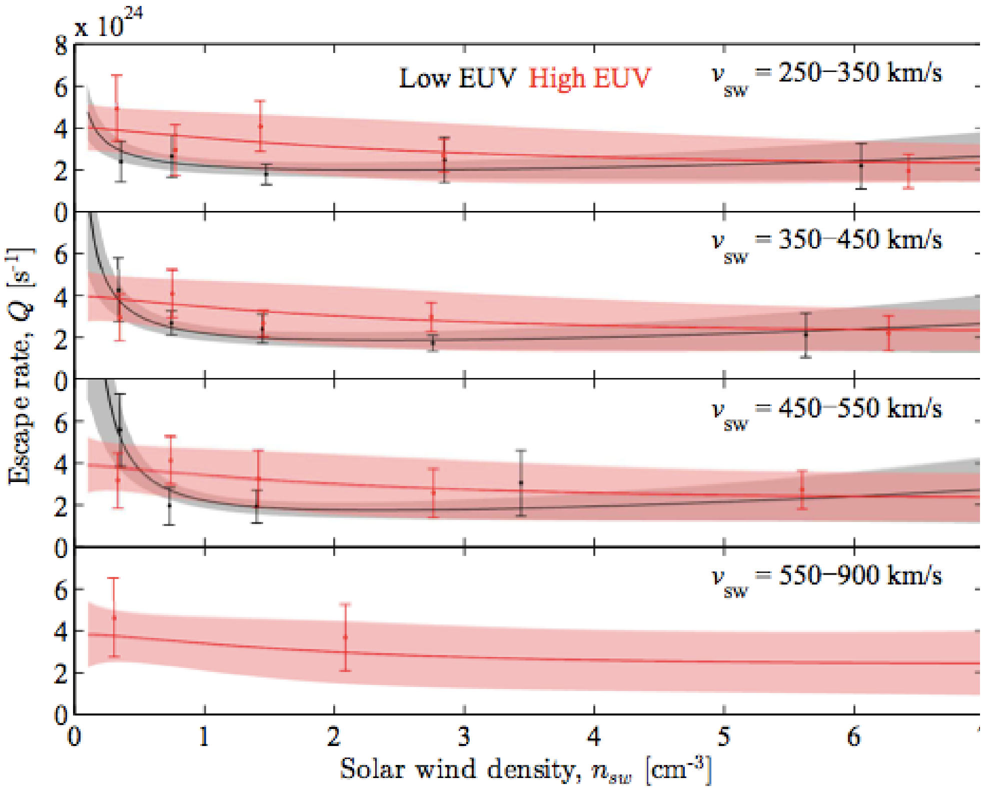
Venus (*VEX*)

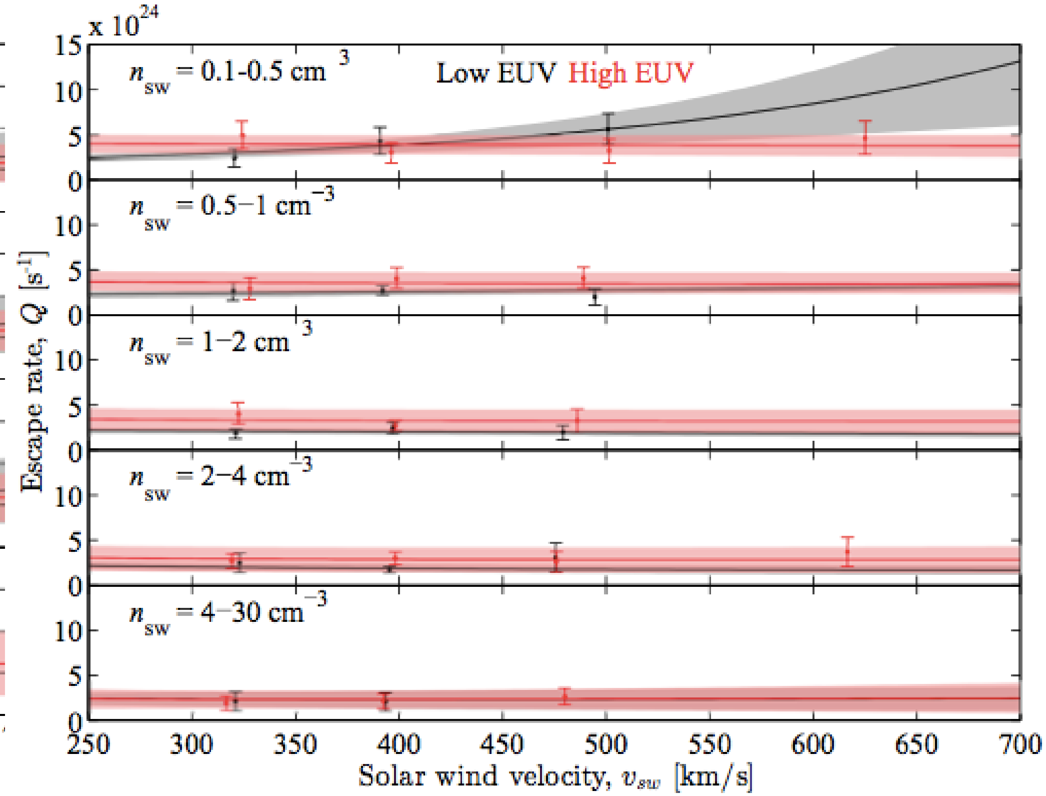


Mars (*MEX*)

Distribution of the planetary ions

Example 1. Escape dependence on the SW parameters



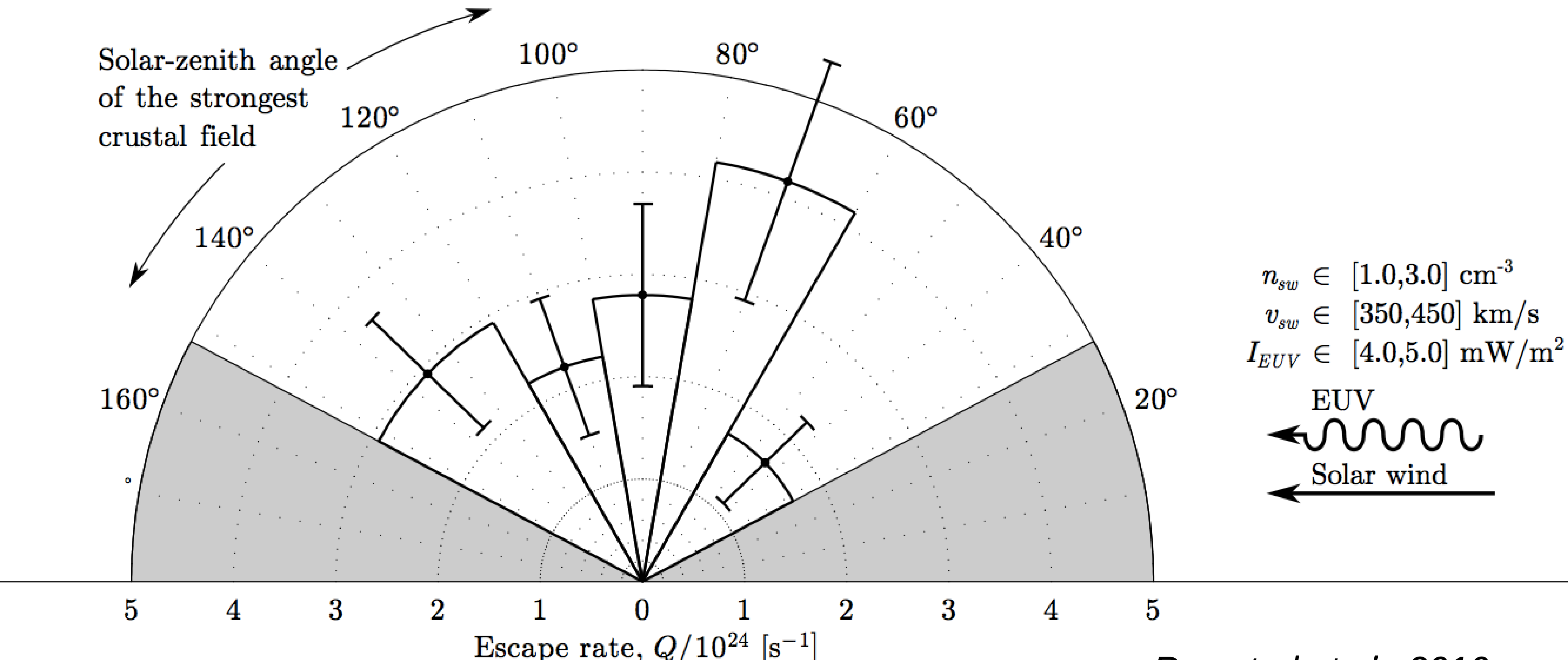


Ramstad et al., 2015

- The highest escape rate $\Phi = 5.6 \times 10^{24}\ s^{-1}$ is observed for thin (0.1-0.5 cm^{-3}) and moderate or high solar wind velocity
  - Largest interaction area
  - Strongest coupling

Example 2. Escape dependence on magnetic anomalies (1)

- Constrained solar wind and EUV flux
- Nominal conditions only to achieve the best statistics
- 8 years of observations 2007-2015

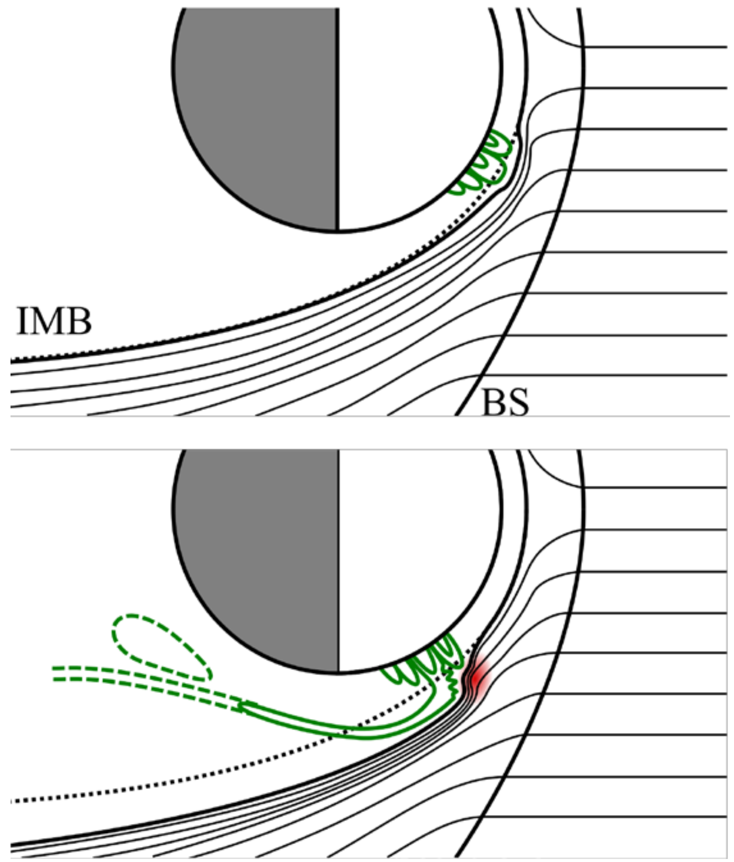


Ramstad et al., 2016

Example 2. Escape dependence on magnetic anomalies (1)

$$A_{interaction} \sim (\rho V^2 \cos^2(SZA))^{-1}$$

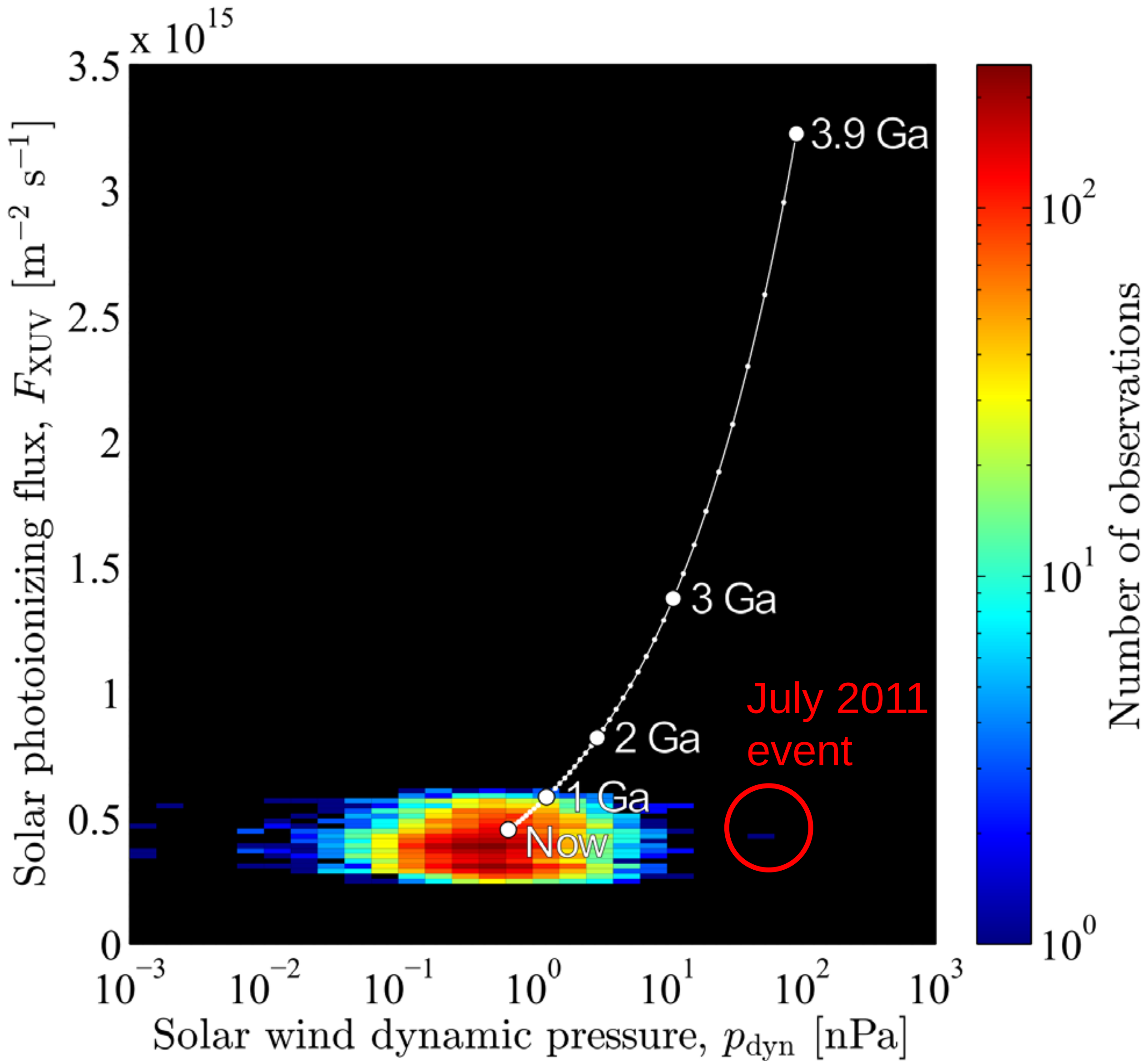
- Small SZA → small $A_{interaction}$ → low escape rate
- Large SZA → IMB above the anomaly region → small/"no" $A_{interaction}$ → low escape



Induced magnetospheres protect Mars and Venus even better than the terrestrial magnetosphere.

But how about the total loss?

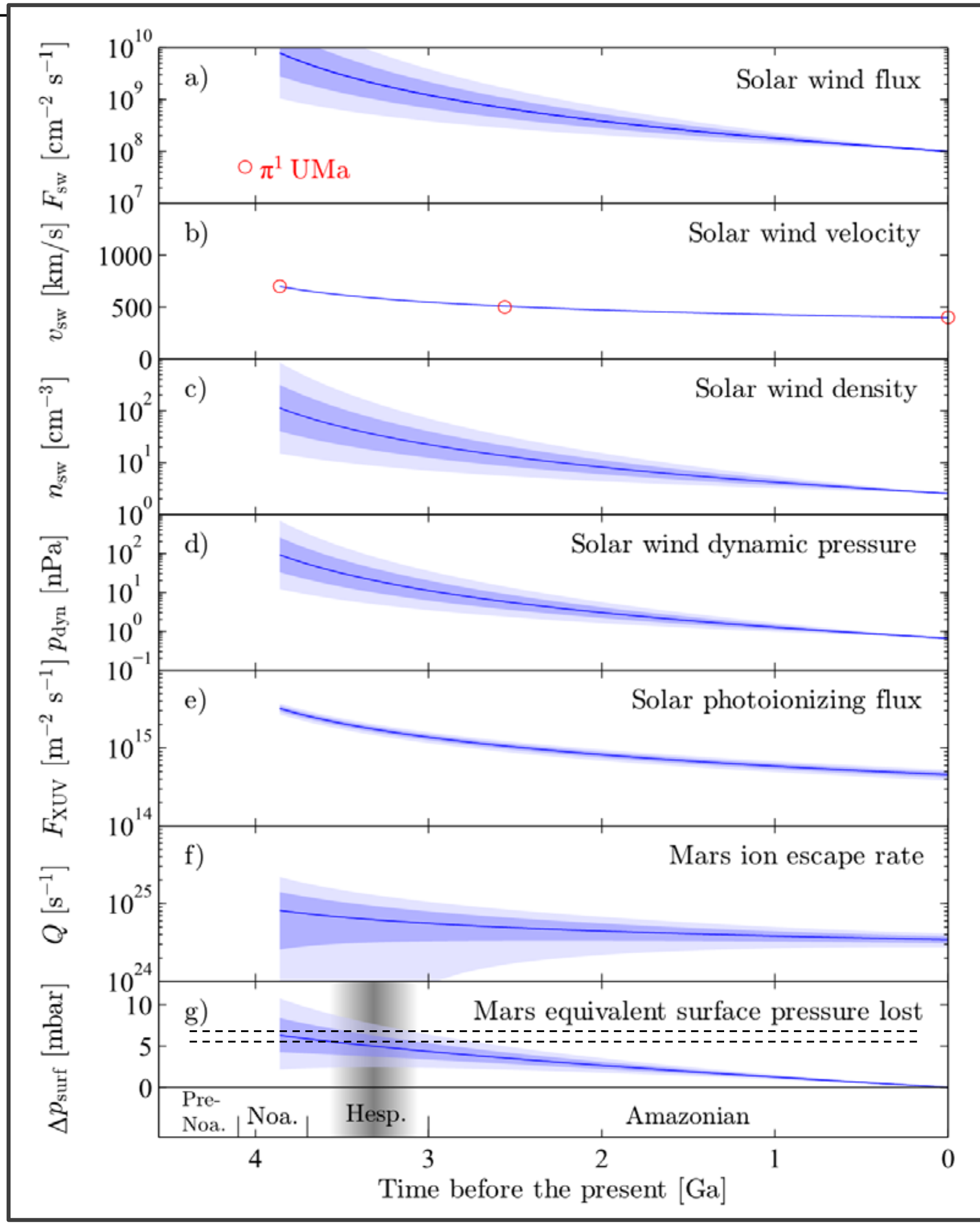
Total atmospheric loss (1). Solar wind and solar conditions



Total atmospheric loss (2). Extrapolation over 4 Ga

- From observations of Sun-like stars
- From theory
- $N_{sw} = F_{sw}/V_{sw}$
- $P_{dyn} = ½\, N_{sw}\, V_{sw}^2$
- From observations of Sun-like stars
- From MEX measurements

$$p_{loss} = \frac{m_{avr}\, g}{A} \int_0^{4Ga} Q(t)\, dt$$



ΔP = 6 mbar

(*Ramstad et al.*, 2018)

The total atmospheric loss for 4 Ga is < 10 mbar. Negligible!

Is it the end?
No! How about the neutral escape?

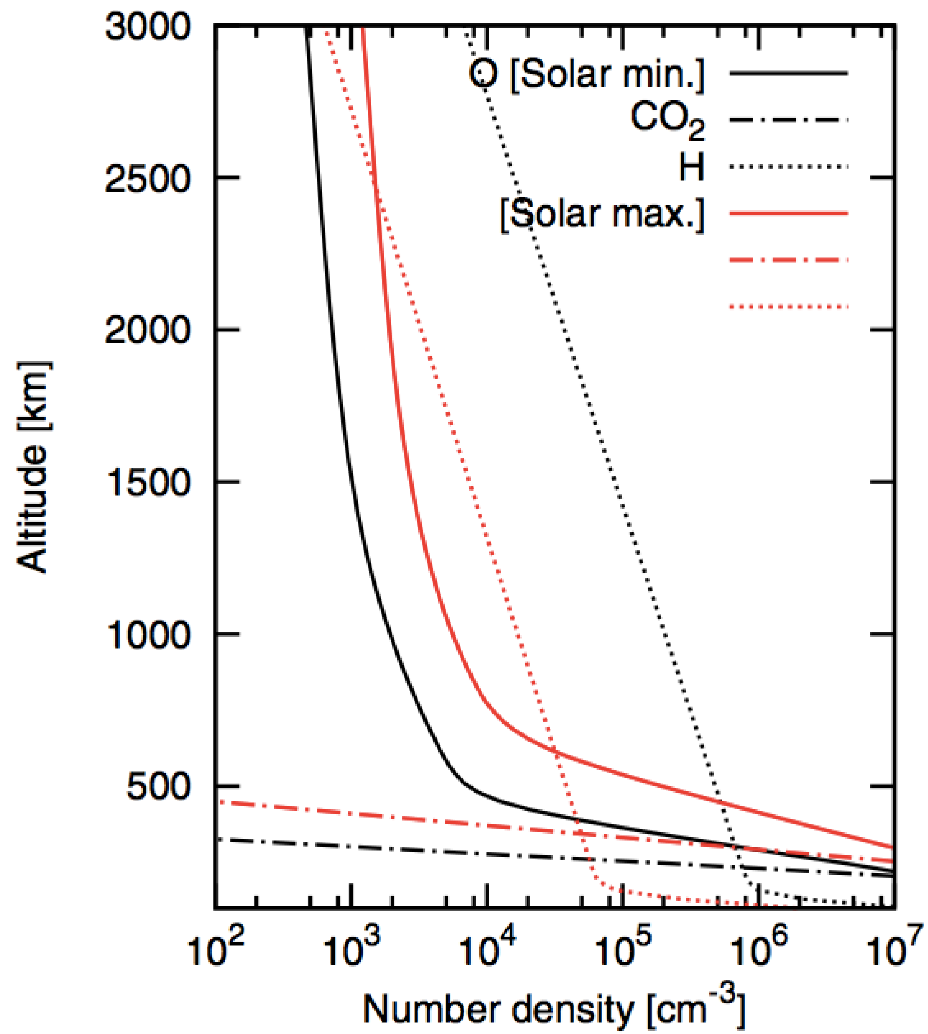
- Atoms/molecules can gain energy above the escape energy in dissociative recombination reactions and elastic collisions building up extended coronae

$$O_2^+ + e \rightarrow O + O + (0.8...7.0\ eV)$$

$$CO_2^+\ e \rightarrow CO + O + 8.3\ eV$$

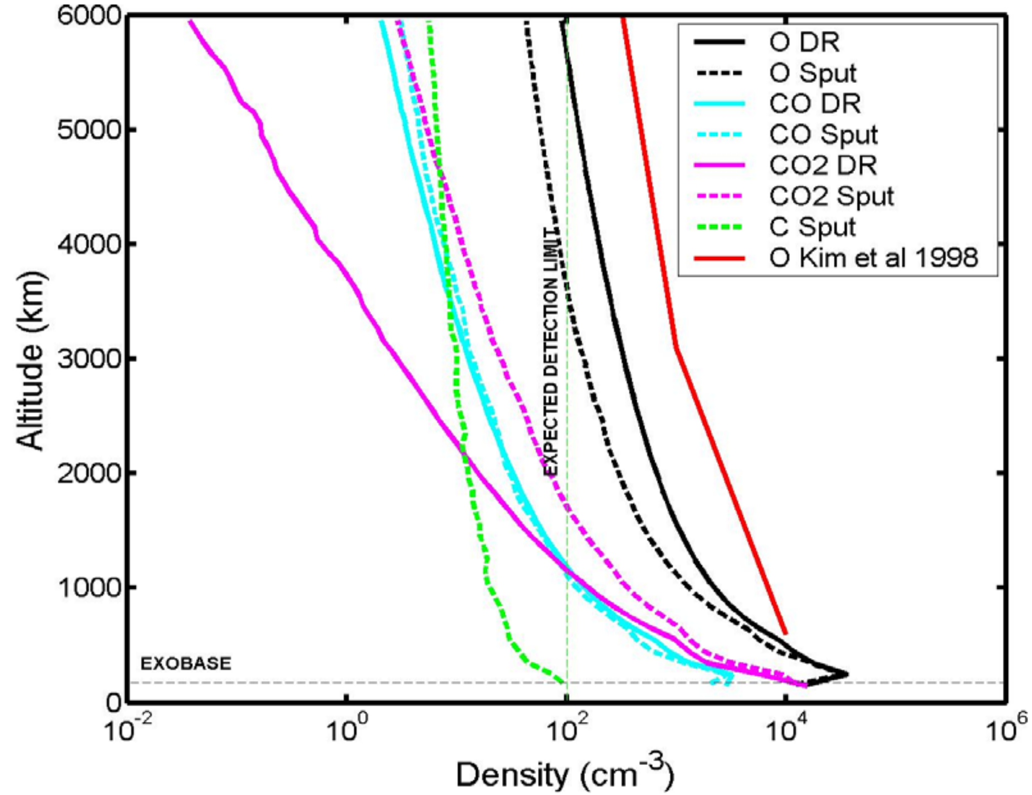
$$H_{th} + O_{hot} \rightarrow H_{hot} + O_{hot}$$

- Only a few eV can be gained. This escape channel is important for Mars only.



Wang et al., 2015 (models)

- Momentum transfer from precipitating (mostly) O^+ ions
- Atmospheric sputtering results in the additional population of the extended hot corona and in the increase of the Jean escape, especially at high levels of solar activity.
- The only channel to remove carbon in the form of CO_2 and CO.



Comparison DR (Dissociative Recombination) and sputtering: 1D models at Solar Max Shematovich, 2006

- Jean escape from hot coronae and sputtering

$$\Phi_J = \frac{N_{ex} v_o}{2\sqrt{\pi}} \left(1 + \lambda_{esc}\right) e^{-\lambda_{esc}}$$

$$\lambda_{esc} = \frac{GMm}{kT(R+z)} = \frac{R+z}{H(z)} = \left(\frac{v_e}{v_o}\right)^2$$

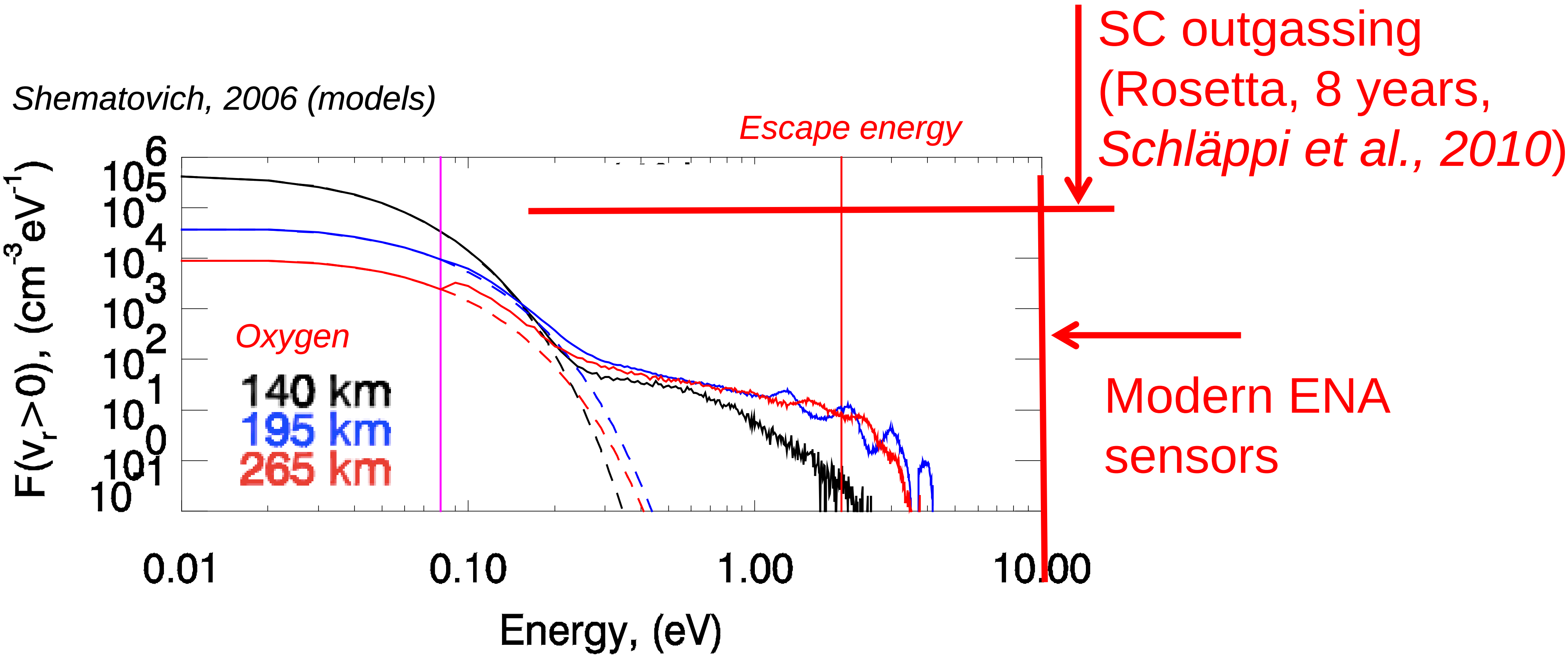
$$v_e = \sqrt{\frac{2GM}{r}}$$

$$v_o = \sqrt{2kT/m}$$

- Measurements of the hot coronae profiles (N_{exo}, T)
  - Difficult due to very low densities. Extensive modeling involved
  - Remote sensing via UV scattered and stimulated emissions (*Dieghan et al., 2015; Chaffin et al., 2015*)
  - Indirect measurements via pick-up H^+ and O^+ flux tracing (*Rahmati et al., 2017*)

Hot H :	$3 \cdot 10^{25}$ s^{-1}	*(measured, Rahmati et al., 2017)*
Hot O :	$7 \cdot 10^{25}$ s^{-1}	*(measured, Rahmati et al., 2017)*
Sputtered CO:	$(1\text{-}4) \cdot 10^{20}$ s^{-1}	*(model, Wang et al., 2015)*
Sputtered CO_2:	$(9\text{-}20) \cdot 10^{21}$ s^{-1}	*(model, Wang et al., 2015)*

Direct measurements of the neutral escape

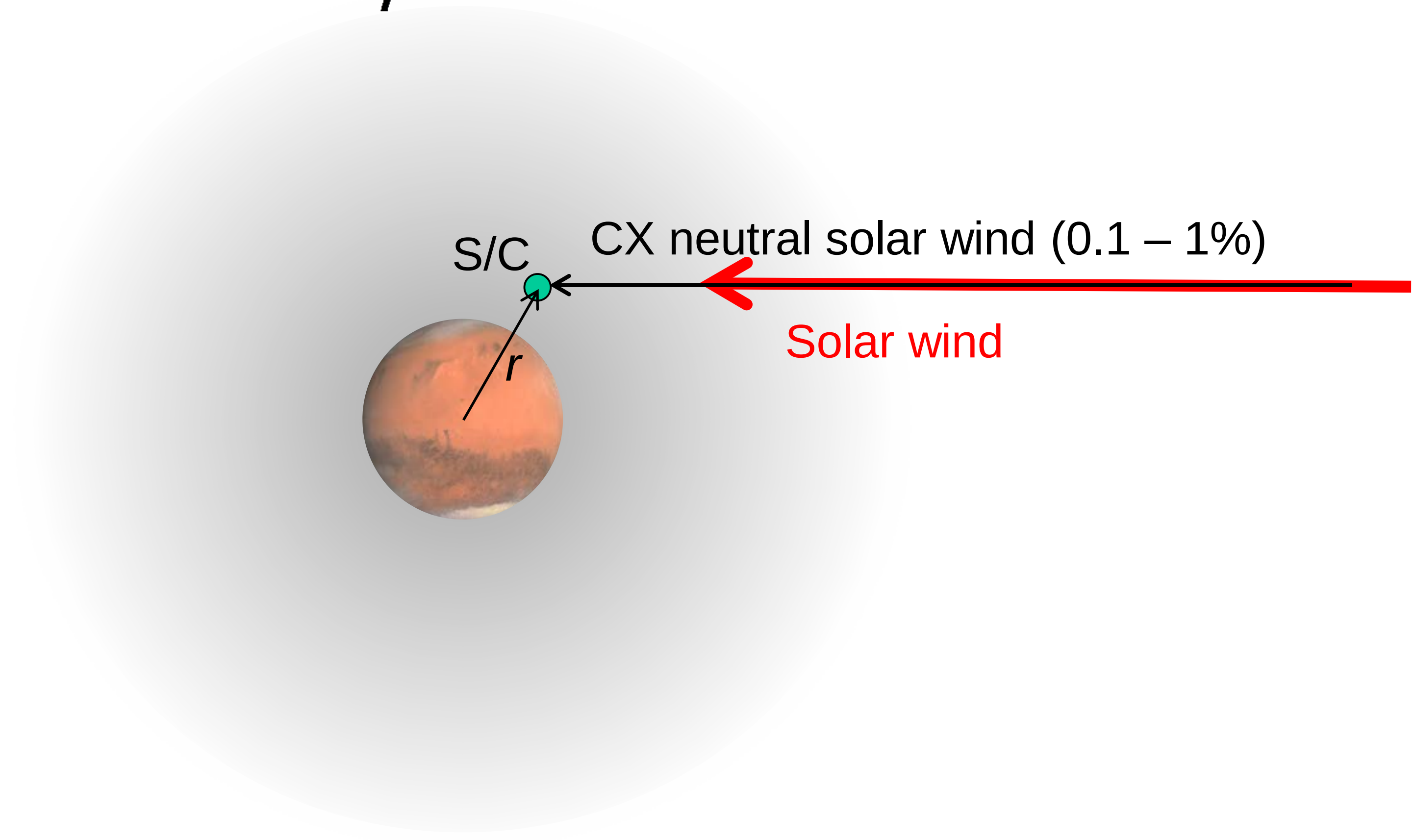


- Direct measurements are very difficult but possible in the future
- New generation of ENA instruments at Mars required

Hot coronae sounding by the neutral solar wind

Upstream solar wind ➛ neutral solar wind

$$F_{neutral} = N_{sw} \; V_{sw} \; \sigma \int_{r}^{\infty} n(l)\,dl = (0.1 - 1\%) \; F_{SW}$$



- Paradigm change: **The intrinsic magnetic field does not protect planetary atmospheres**

- The atmospheric loss associated with ion escape is low (< 10 mbar) for Mars (and likely for Venus)

- The neutral escape is by far more important channel
- New measurements techniques based on ENA measurements can be applied to better characterized the neutral escape