Non-thermal Atmospheric Erosion Processes

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Europlanet Workshop, Romania, June 2018

Outline

- Examples of planetary objects subject of atmospheric erosion

- Classification of Loss Processes

- Thermal Escape

    Jeans Escape
    Hydrodynamic Escape

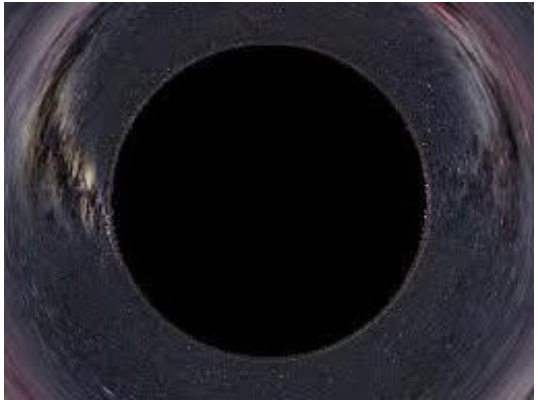
- Non-thermal Escape

    Pickup
    Chemical Escape

Examples

They lose everything:

They lose nothing:

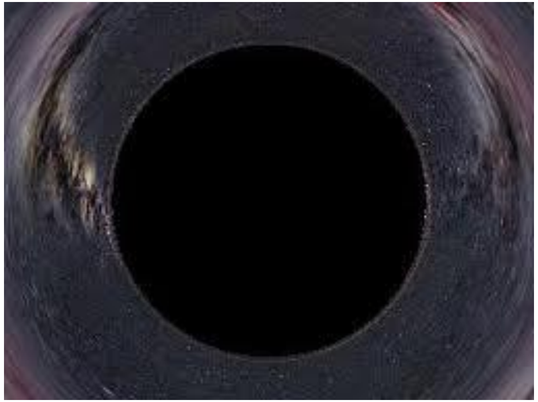


Examples

They lose everything:

They lose something:

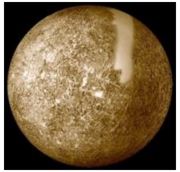
They lose nothing:



Diversity of Atmospheres

Earth: 1bar, 300K, N_2, O_2

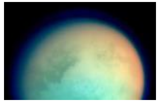
Venus: 92bar, 700K, CO_2



Mercury: exosphere (traces of Na)

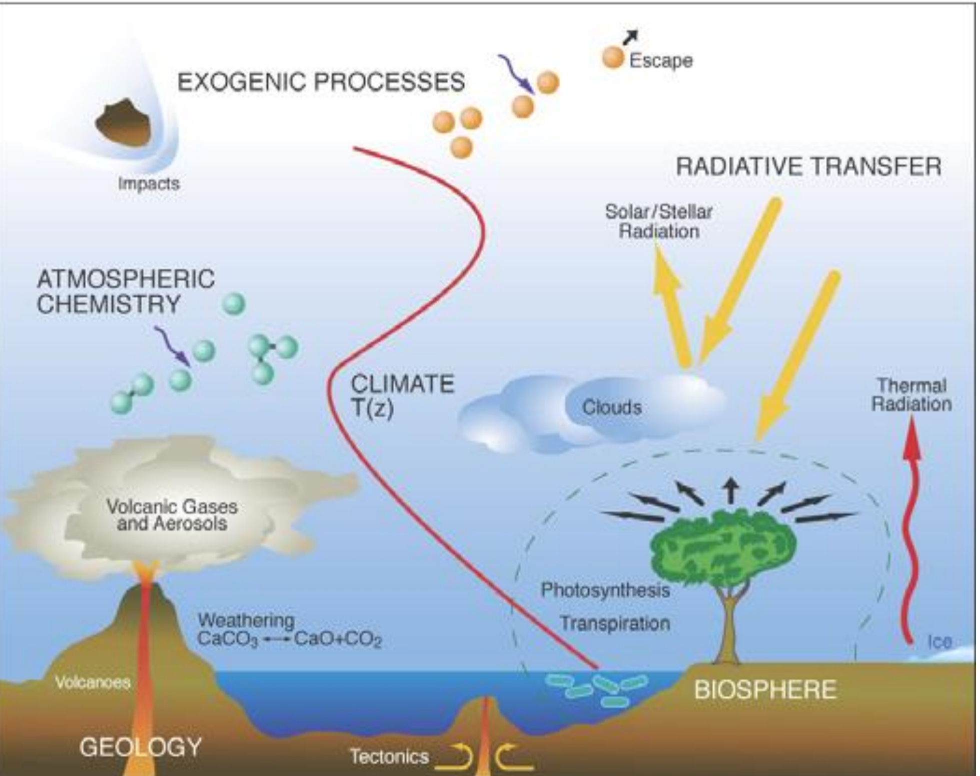
Mars: 6mbar, 200K, CO_2

Callisto: $<10^{-11}$bar, CO_2



Titan: 1.5bar, 94K, N_2

Classification of Atmospheric Loss Processes



Loss to Space:
Escape

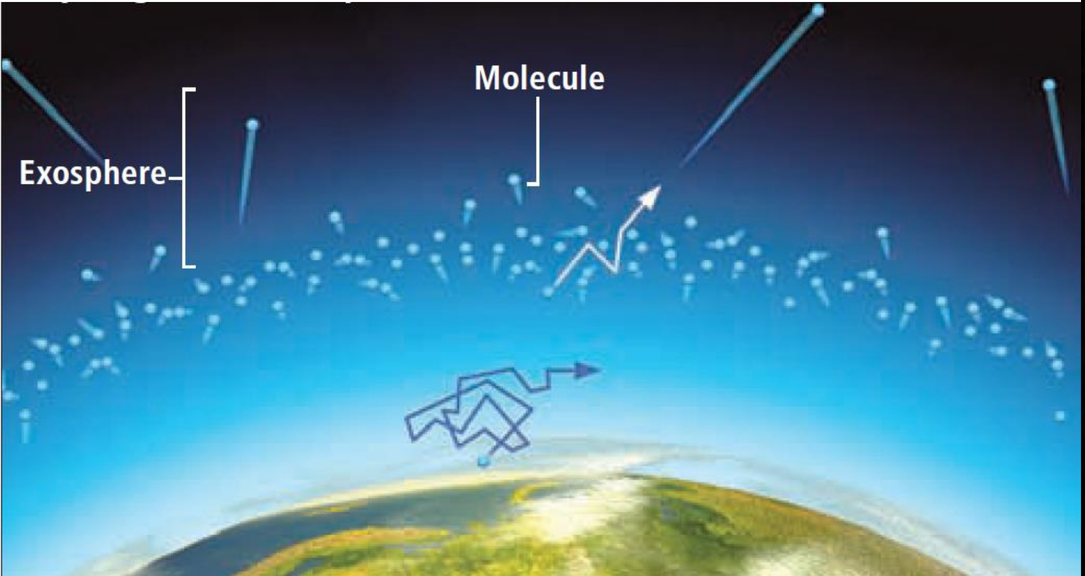
Thermal
- Jeans
- Hydrodynamic

Non-Thermal
- Pickup
- Chemical

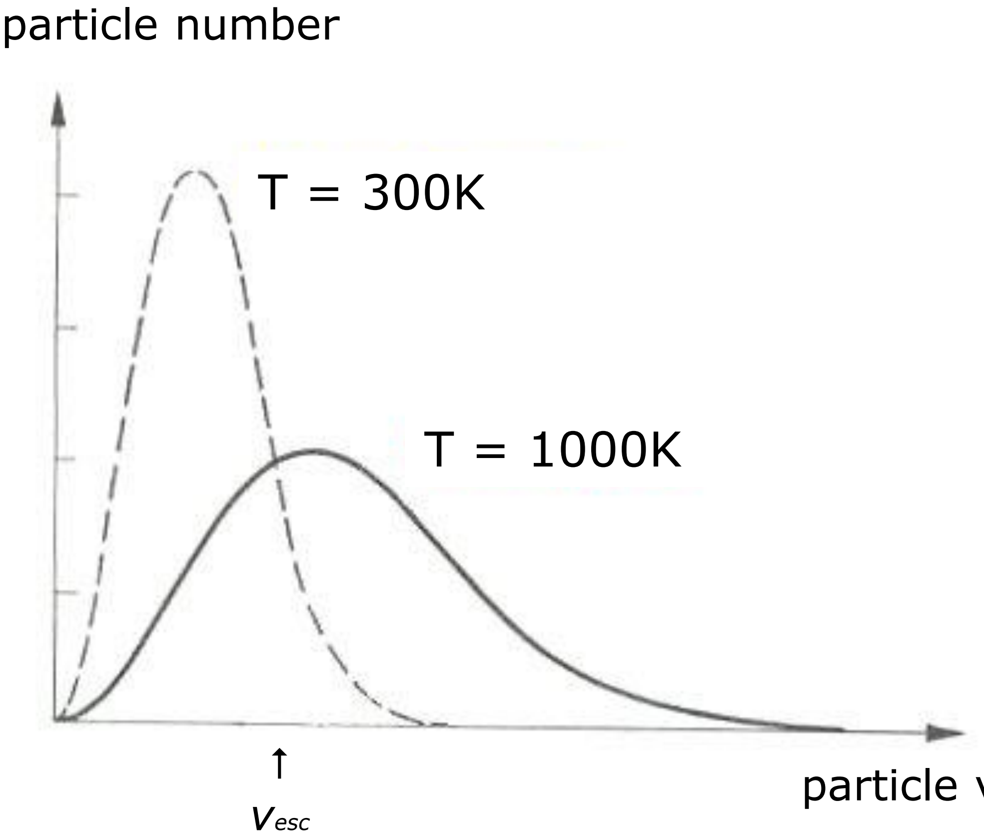
Loss to Surface:
Sequestration

Jeans Escape vs. Hydrodynamic Escape

Jeans



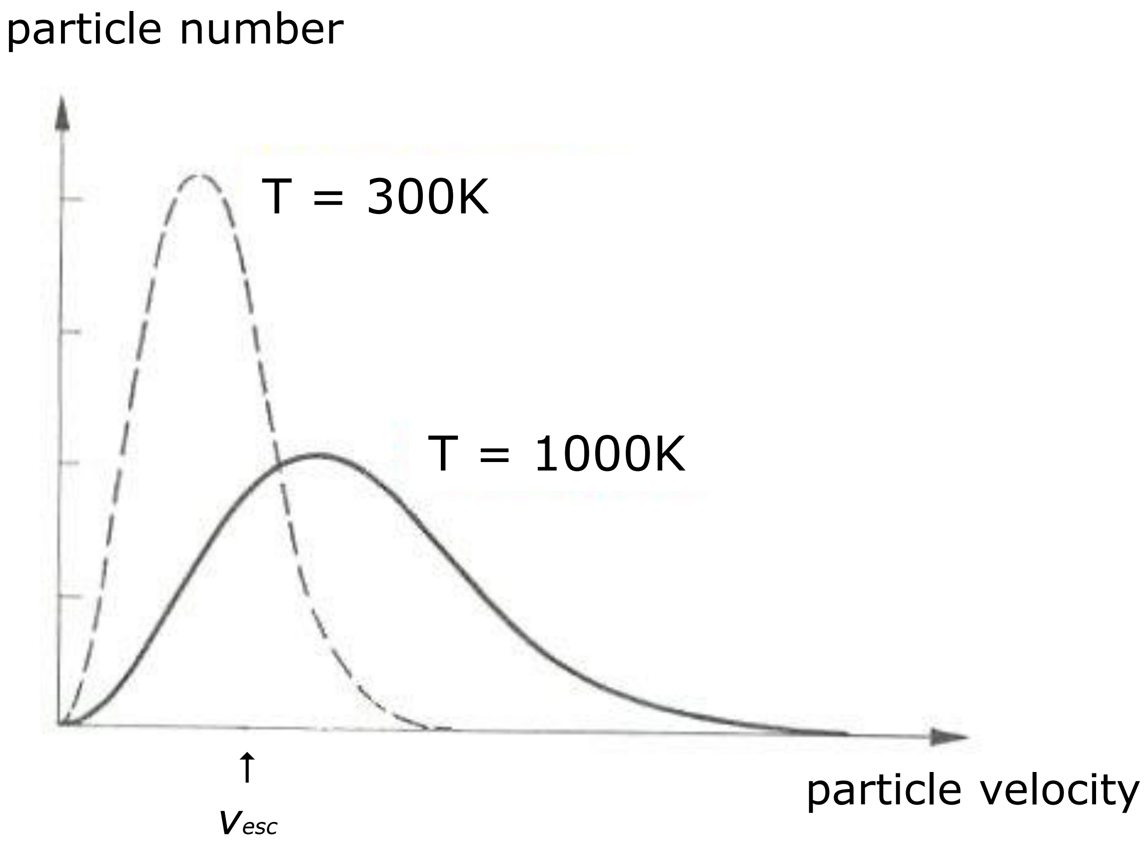
Jeans Escape vs. Hydrodynamic Escape



Escape velocity: $v_{esc} = \sqrt{\frac{2GM}{R}}$

Peak velocity: $v_{peak} = \sqrt{\frac{2kT}{m}}$

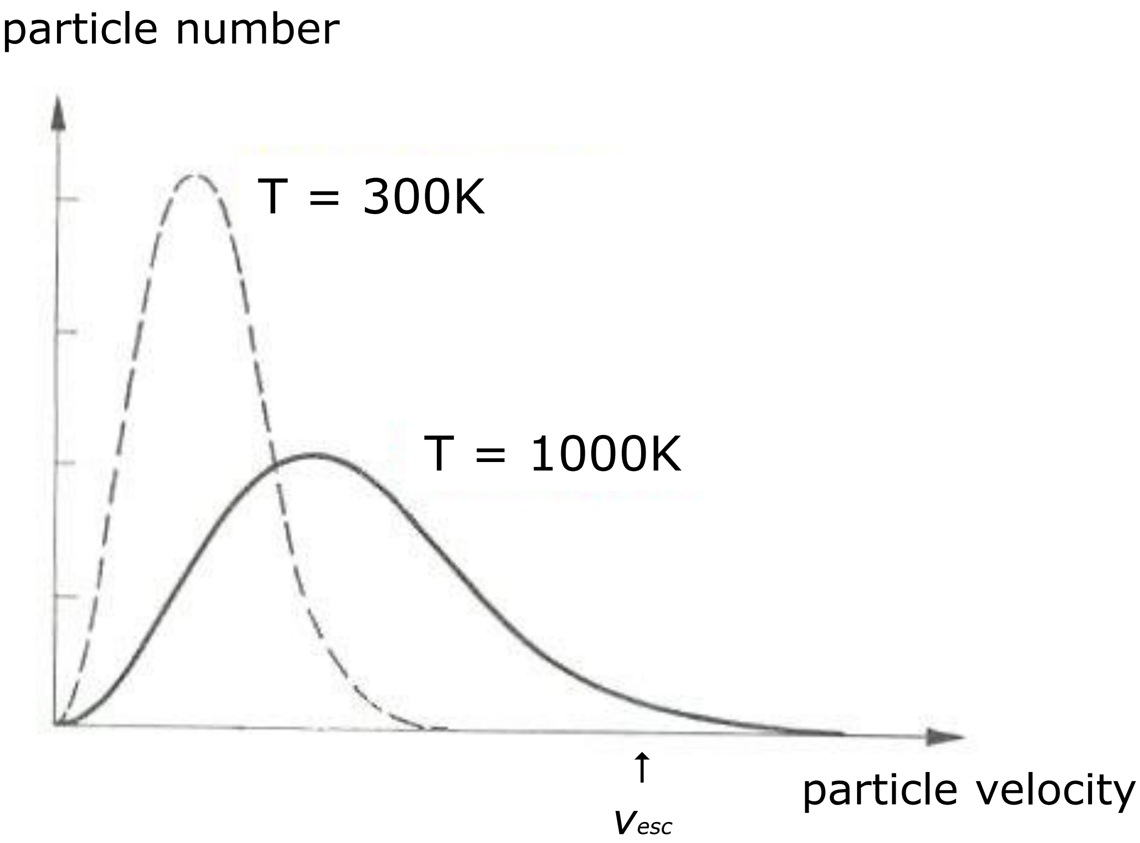
Escape Velocity vs. Peak Velocity

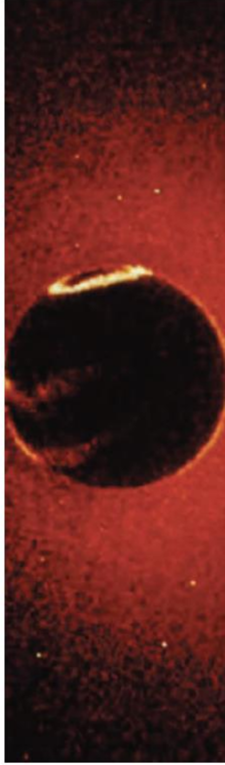


- Escape velocity:
  - Earth: 11 km/s
  - Venus: 10 km/s
  - Mars: 5 km/s
  - Titan: 2.1 km/s
  - Pluto: 1.2 km/s
  - 67P/CG: 1 m/s

- Peak velocity
  - H, 300K: 2 km/s
  - H, 1000K: 4 km/s
  - N_2, 300K: 0.4 km/s
  - N_2, 100K: 0.2 km/s
  - CO_2,100K: 0.16 km/s
  - CH_4, 50K: 0.2 km/s

Thermal Escape at Earth: Jeans, H





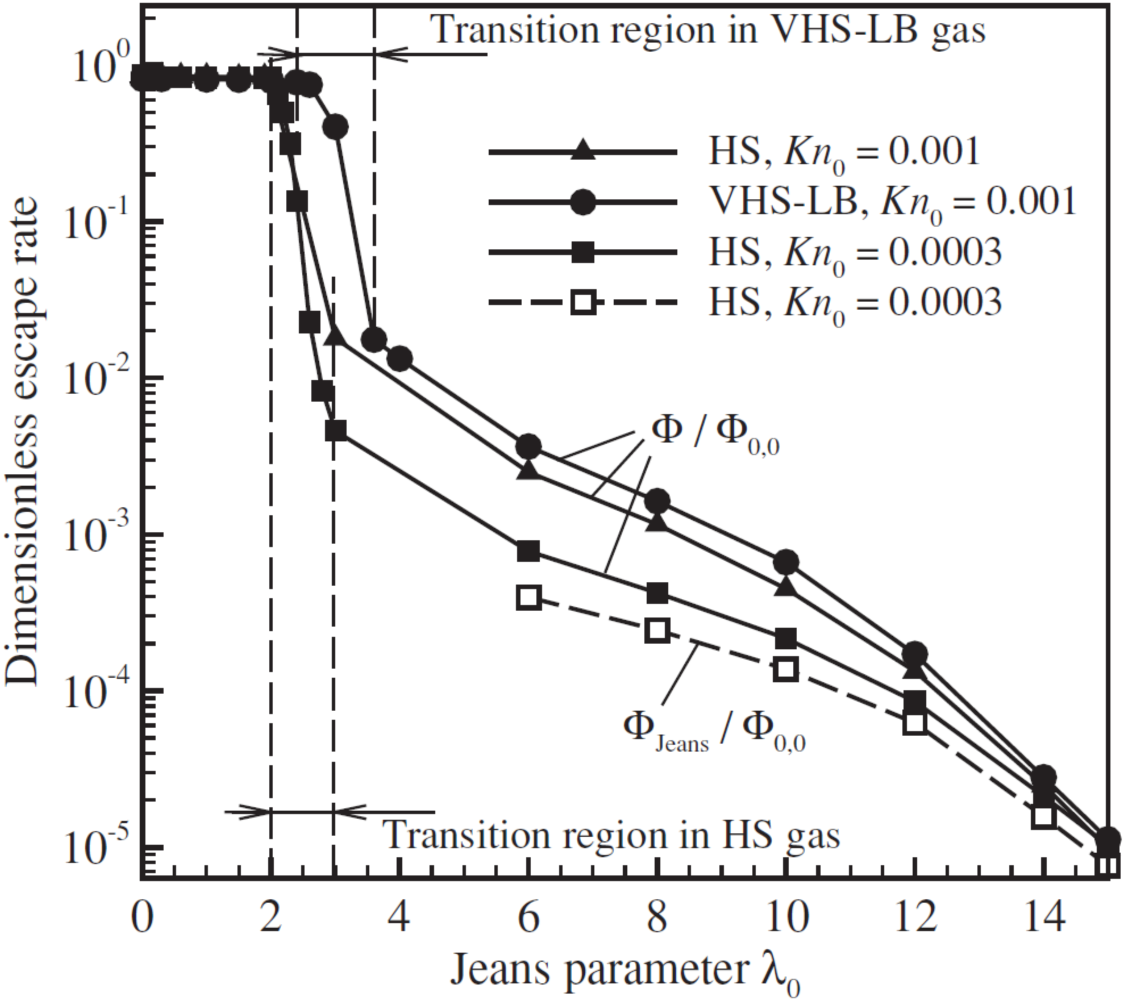
LEAKING HYDROGEN ATOMS give off a red glow in this ultraviolet image of Earth's night side, taken by NASA's Dynamic Explorer I satellite in 1982. Oxygen and nitrogen account for the band around the North Pole and the wisps in the tropics.

[Catling & Zahnle, 2009]

- Today: Only H Jeans Escape
  - Earth: 3 kg/s = 3 10^{27} /s
  - Mars: ~ 10^{26} /s
  - Venus: << 10^{26} /s

Jeans Parameter λ_0

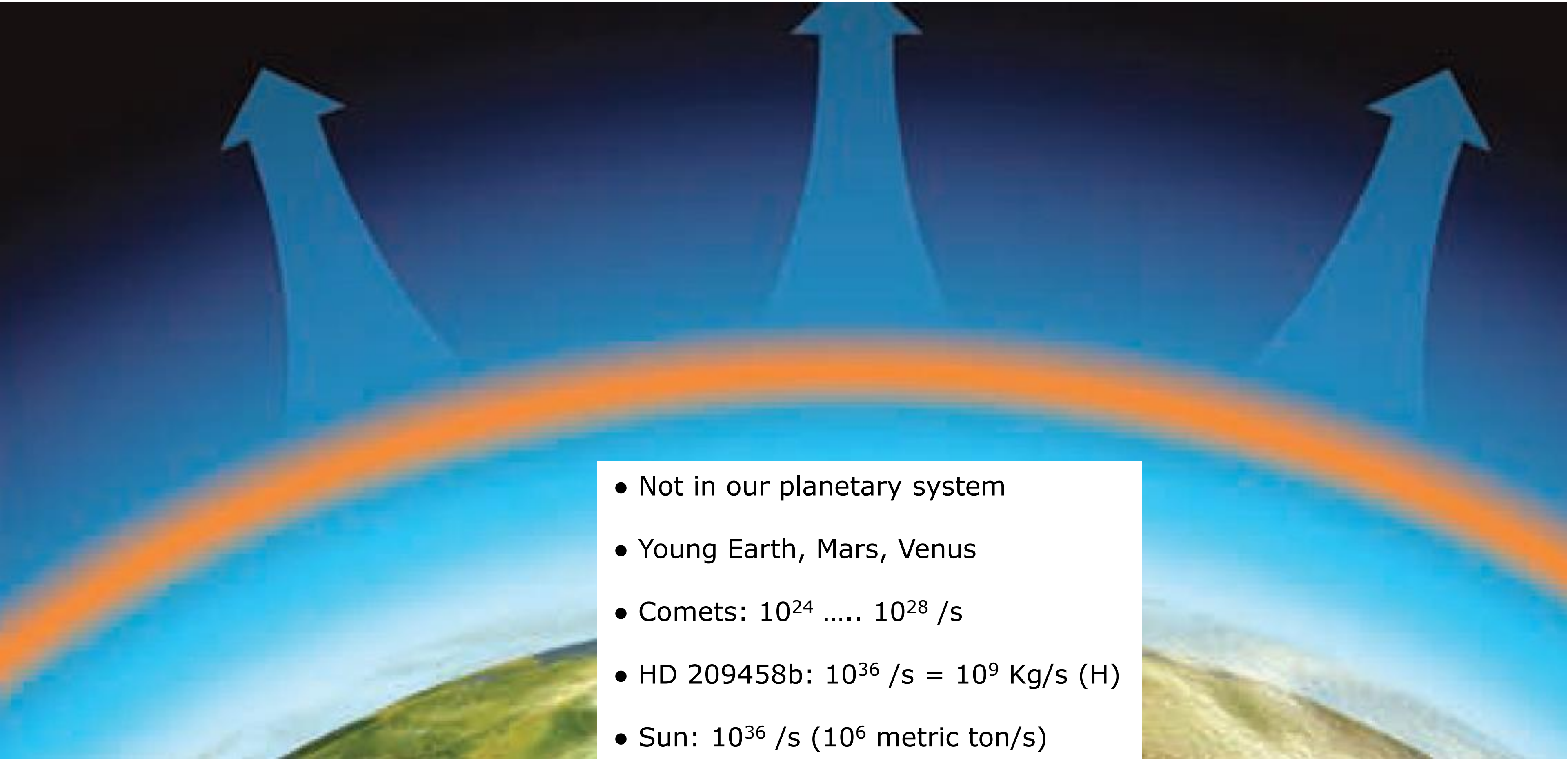
$$\lambda_0 = \left(\frac{v_{esc}}{v_{peak}}\right)^2 = \frac{GMm/R}{kT}$$



[Volkov et al, 2008]

Hydrodynamic Escape

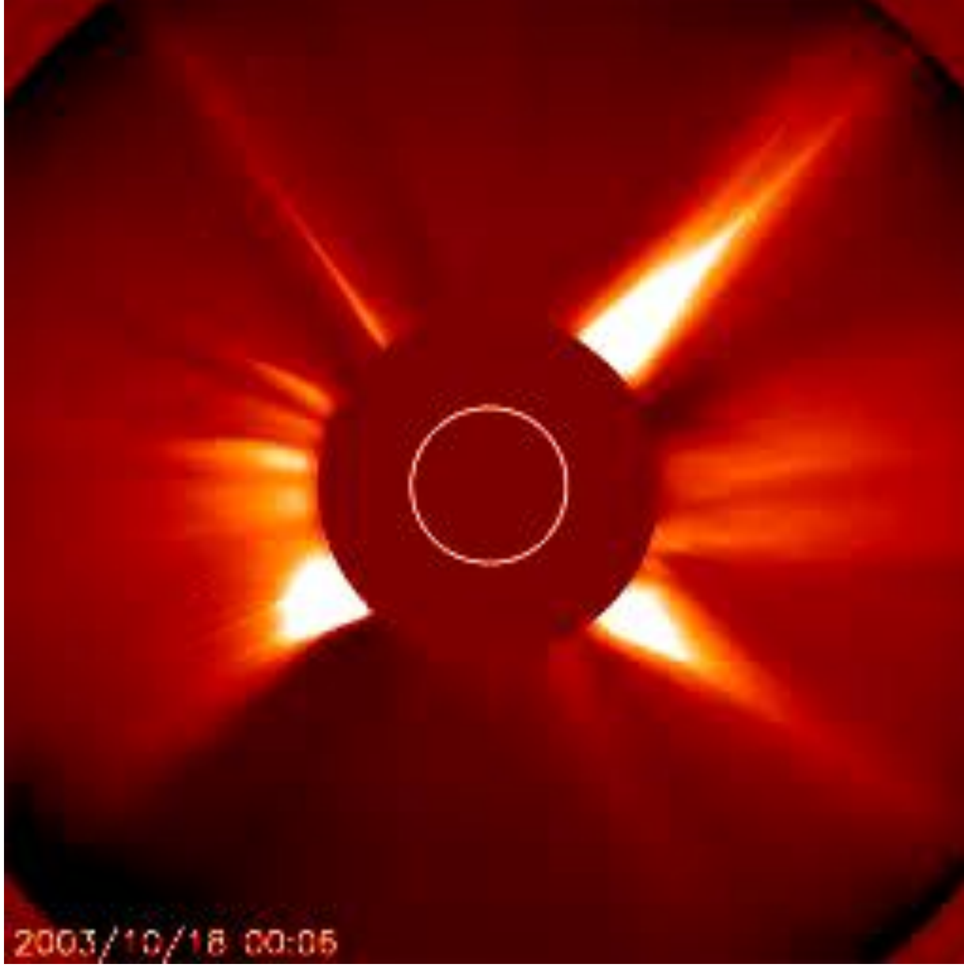
[Vidal-Madjar et al.; Nature, 2003]



- Not in our planetary system
- Young Earth, Mars, Venus
- Comets: 10^{24} ….. 10^{28} /s
- HD 209458b: 10^{36} /s = 10^{9} Kg/s (H)
- Sun: 10^{36} /s (10^{6} metric ton/s)

Solar Hydrodynamic Escape: Solar Wind

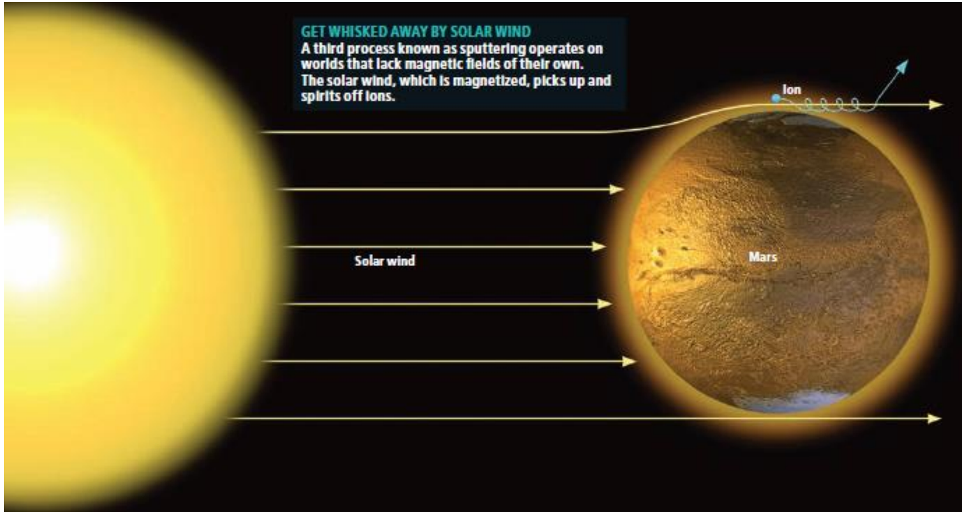
- Atmosphere = Corona: $T_{corona} \sim 10^6$ K
- Parker model
- 10^{36} /s ~ 1 Megaton / s



[http://sohowww.estec.esa.nl/]

Pickup

- Interaction of Solar Wind with ionospheric ions
- Pulling out and incorporating ions in the Solar Wind
- Electromagnetic plasma effect
- Collisionless
- Operating where Solar Wind overlaps ionosphere
- Nearly no pickup at Earth
- Pickup at Mars, Venus, Pluto, Titan
- Pickup at comets, but ….



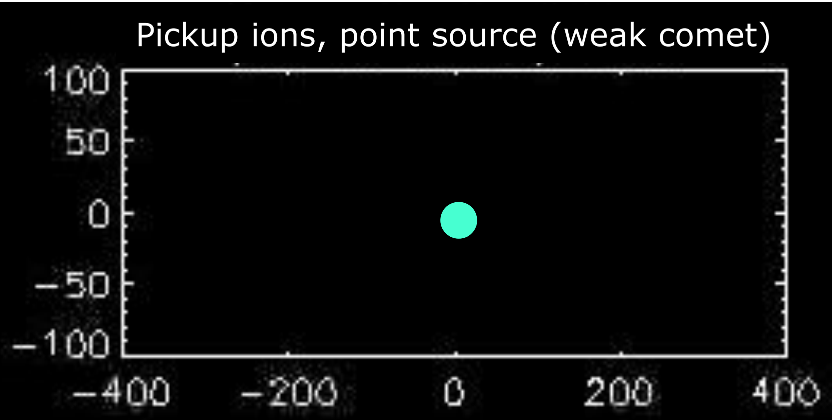
GET WHISKED AWAY BY SOLAR WIND
A third process known as sputtering operates on worlds that lack magnetic fields of their own. The solar wind, which is magnetized, picks up and spirits off ions.

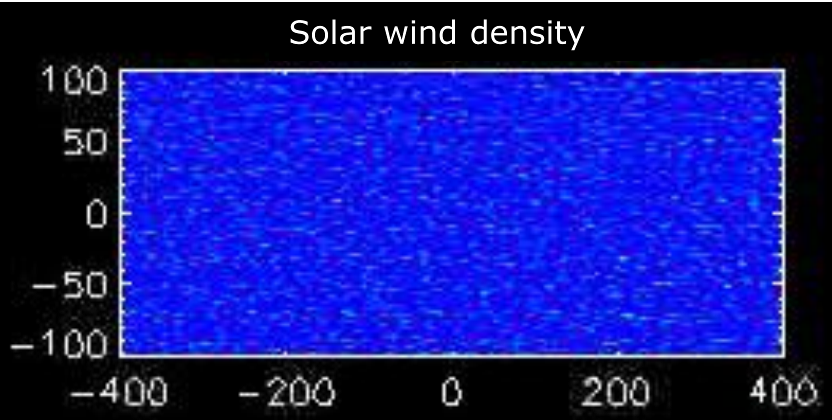
Pickup at Mars vs. comets

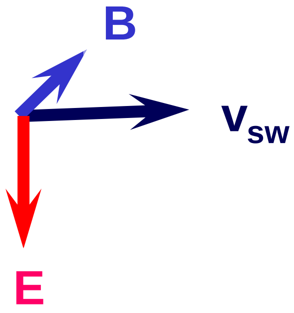
- Mars has a hydrodynamically stable atmosphere/ionosphere
- Without Solar Wind no loss

- Comets have hydrodynamically unstable atmospheres/ionospheres
- Without Solar Wind it would be lost nevertheless
- Pickup at comets is a subsequent process but not the primary loss process

Pickup of test particles from point source

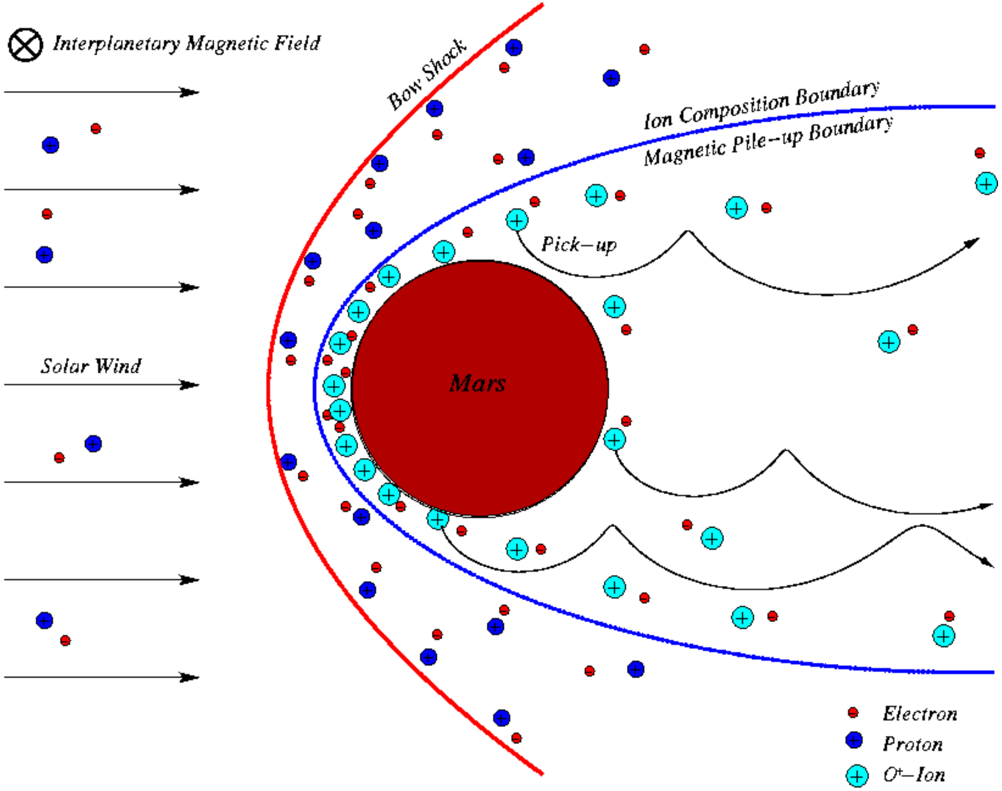

Pickup ions, point source (weak comet)


Solar wind density



$$\frac{d\vec{v}_s}{dt} = \frac{q_s}{m_s}(\vec{E} + \vec{v}_s \times \vec{B})$$

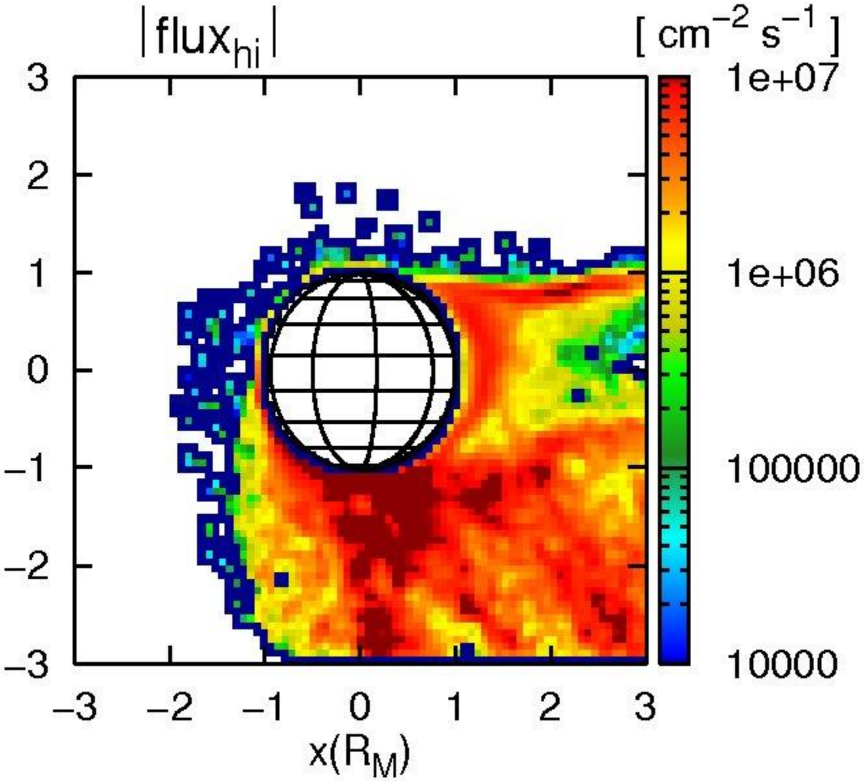
Pickup at Mars



Adaptive Ion Kinetic Electron Fluid Simulation Code

[Boesswetter & Motschmann, 2010]

Pickup at Mars

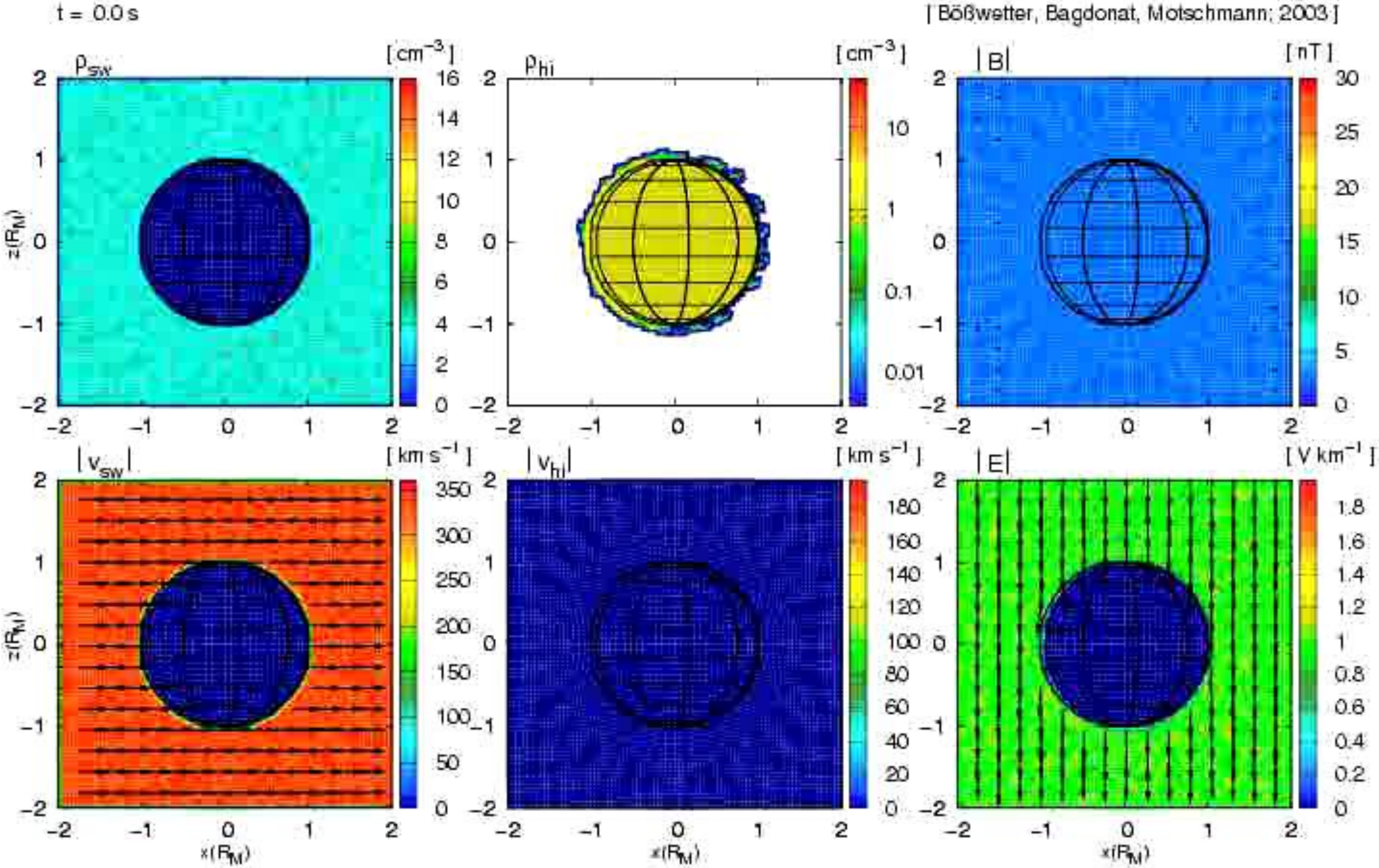


Integral flux (O^+, O_2^+ , CO_2^+)

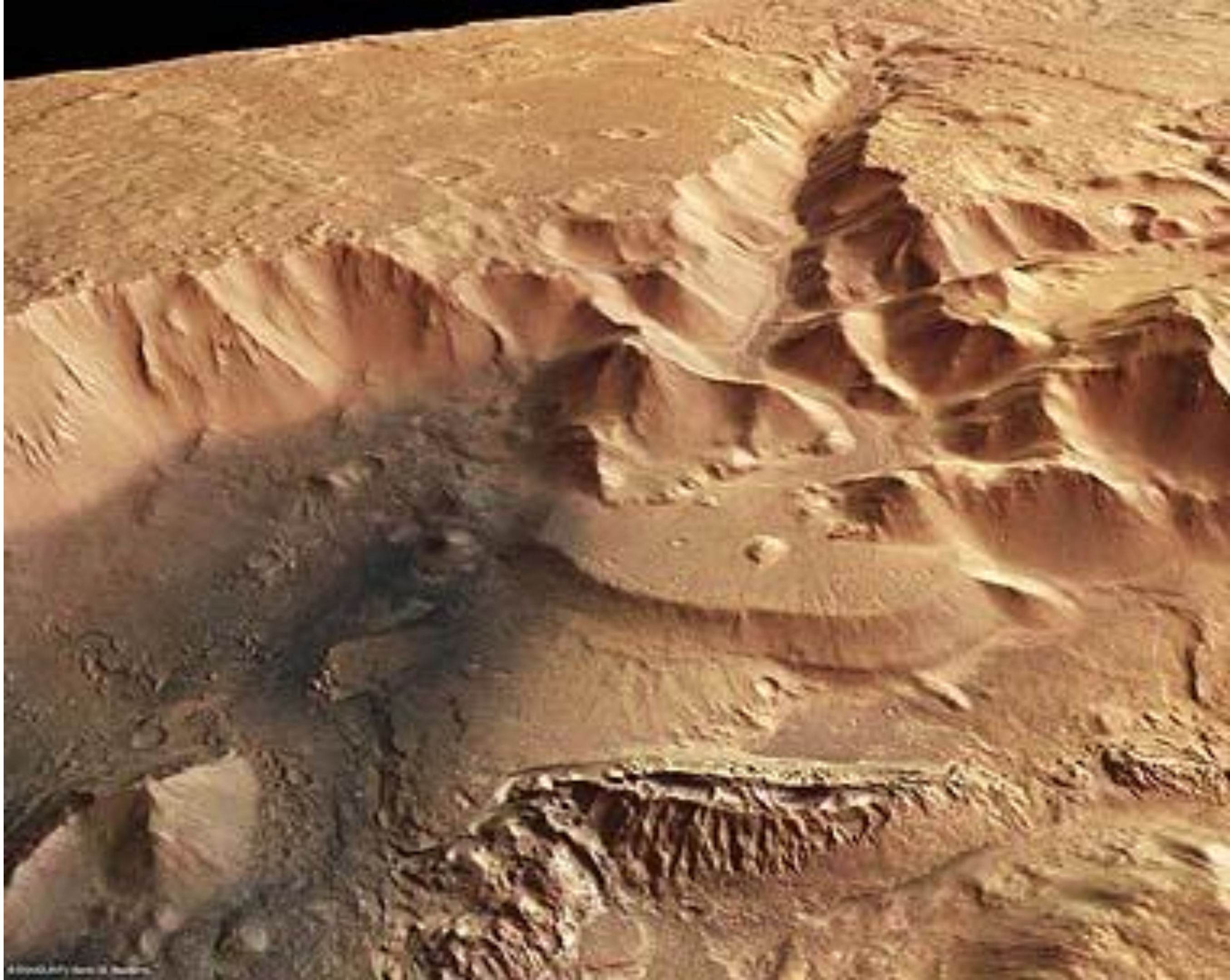
MEX at solar minimum

[Boesswetter & Motschmann, 2010]

Pickup at Mars

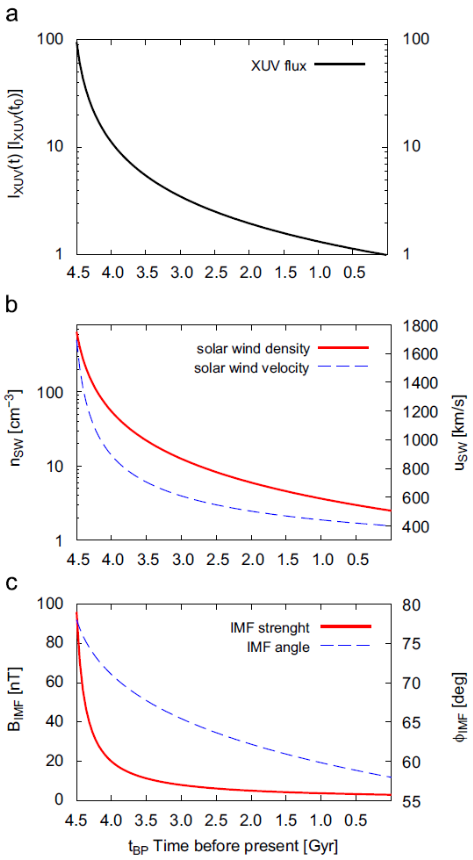


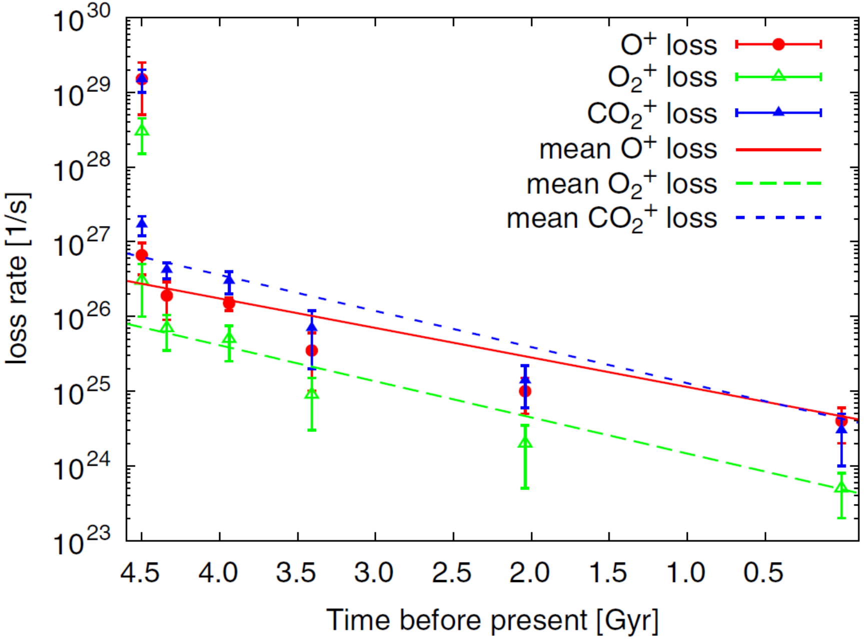
Loss by Pickup at Mars



River delta in Nepenthes Mensae
[www.dlr.de]

Loss by Pickup at Mars





$\Delta S_{\mathrm{mean}}(\mathrm{H_2O}) = 0.9$ m during the last 3.5 Gyr,

$\Delta S_{\mathrm{mean}}(\mathrm{H_2O}) = 2.6$ m during the last 4.5 Gyr,

$\Delta S_{\mathrm{max}}(\mathrm{H_2O}) = 205$ m during the first 0.15 Gyr.

[Ribas et al., ApJ, 2005]

[Boesswetter & Motschmann, PSS,2010]

Pickup at Venus

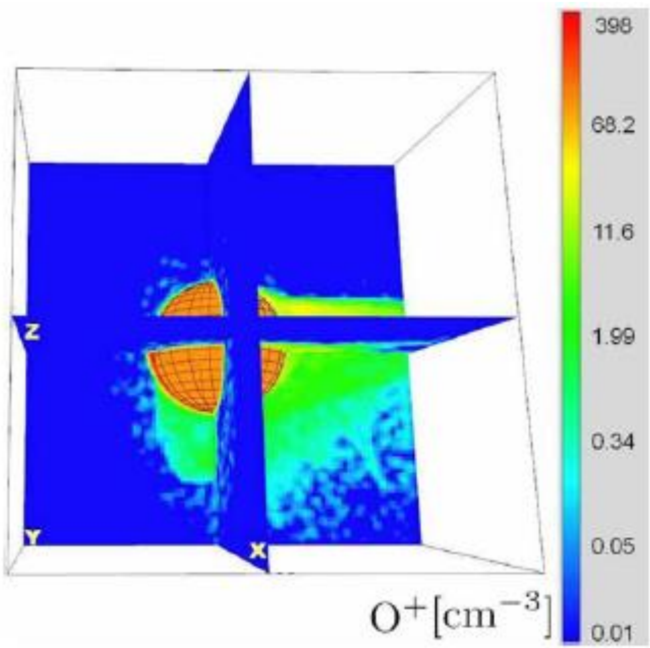
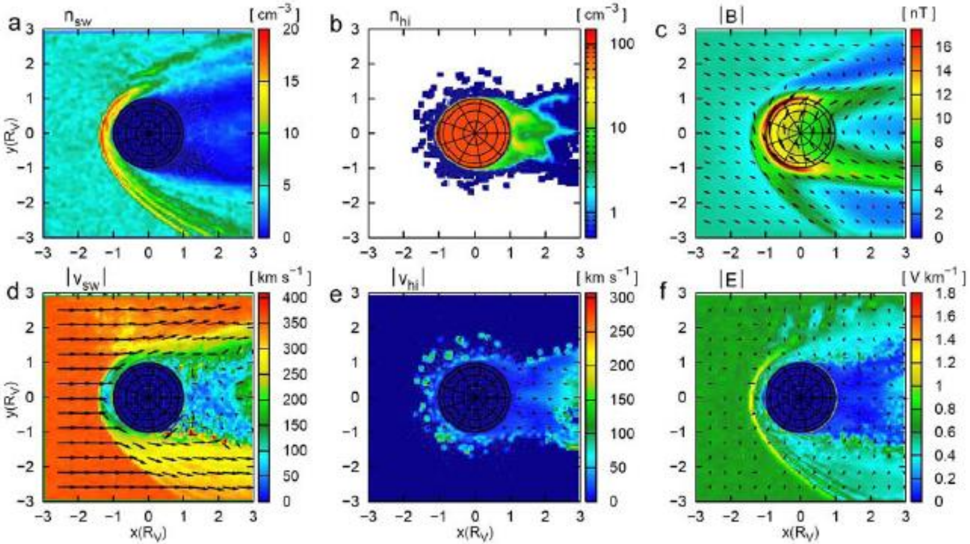


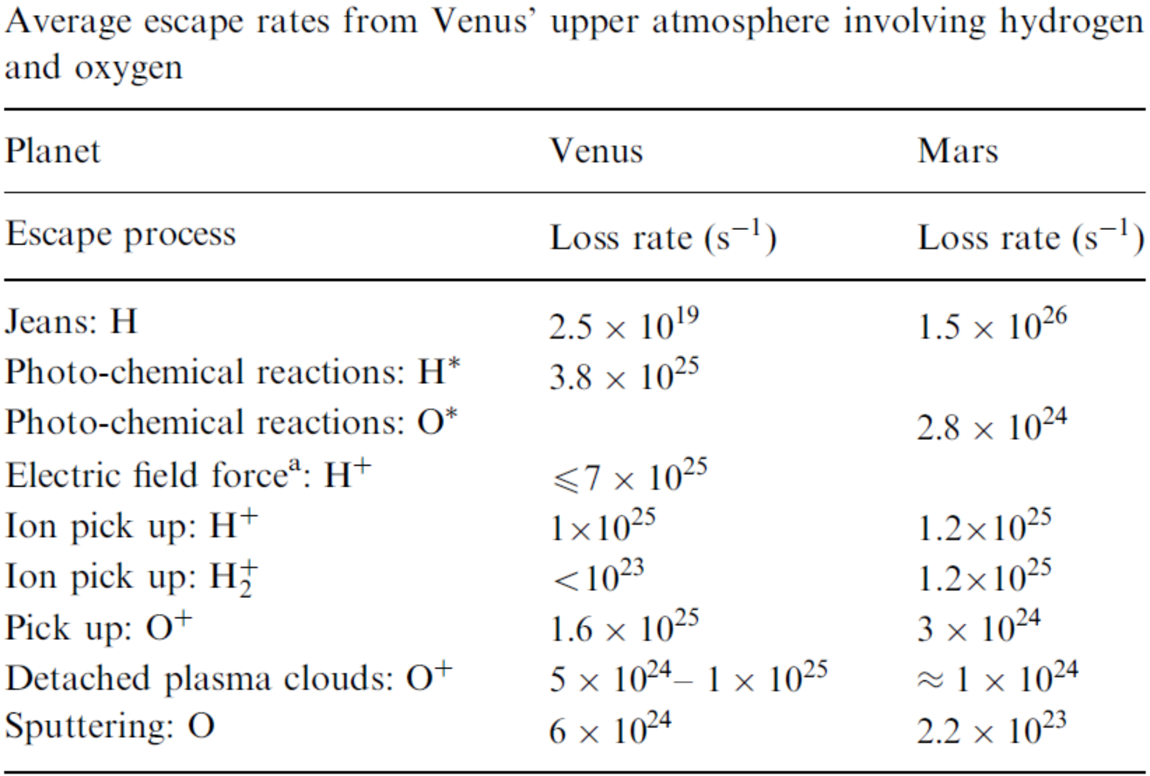
Figure 8. Global 3-D view of simulation results showing the heavy ion density (O^+) (cm^{-3}). The cutting planes through the simulation box are taken at $x = 0$ (terminator plane), $y = 0$ (polar plane), and $z = 0$ (equatorial plane).



- O^+ loss rate: 9×10^{25} /s

[Martinecz & Motschmann, JGR, 2009]

Pickup at Venus



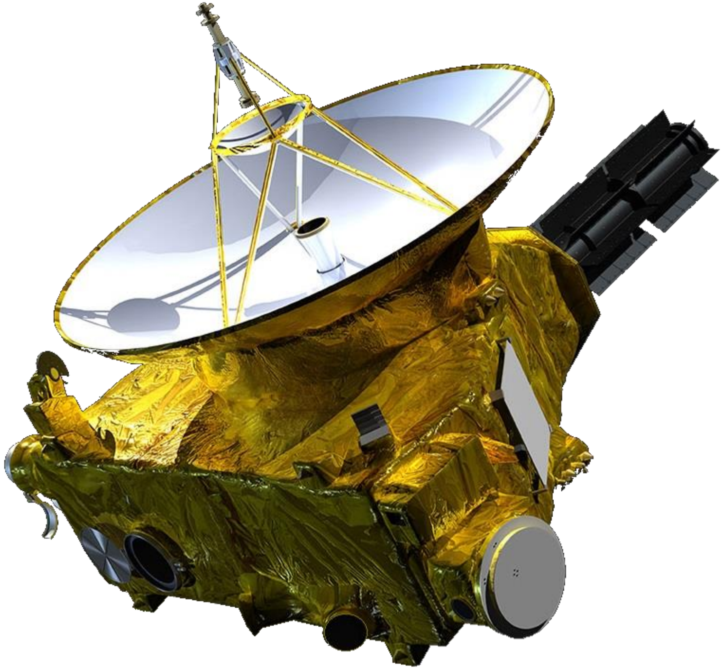
Average escape rates from Venus' upper atmosphere involving hydrogen and oxygen

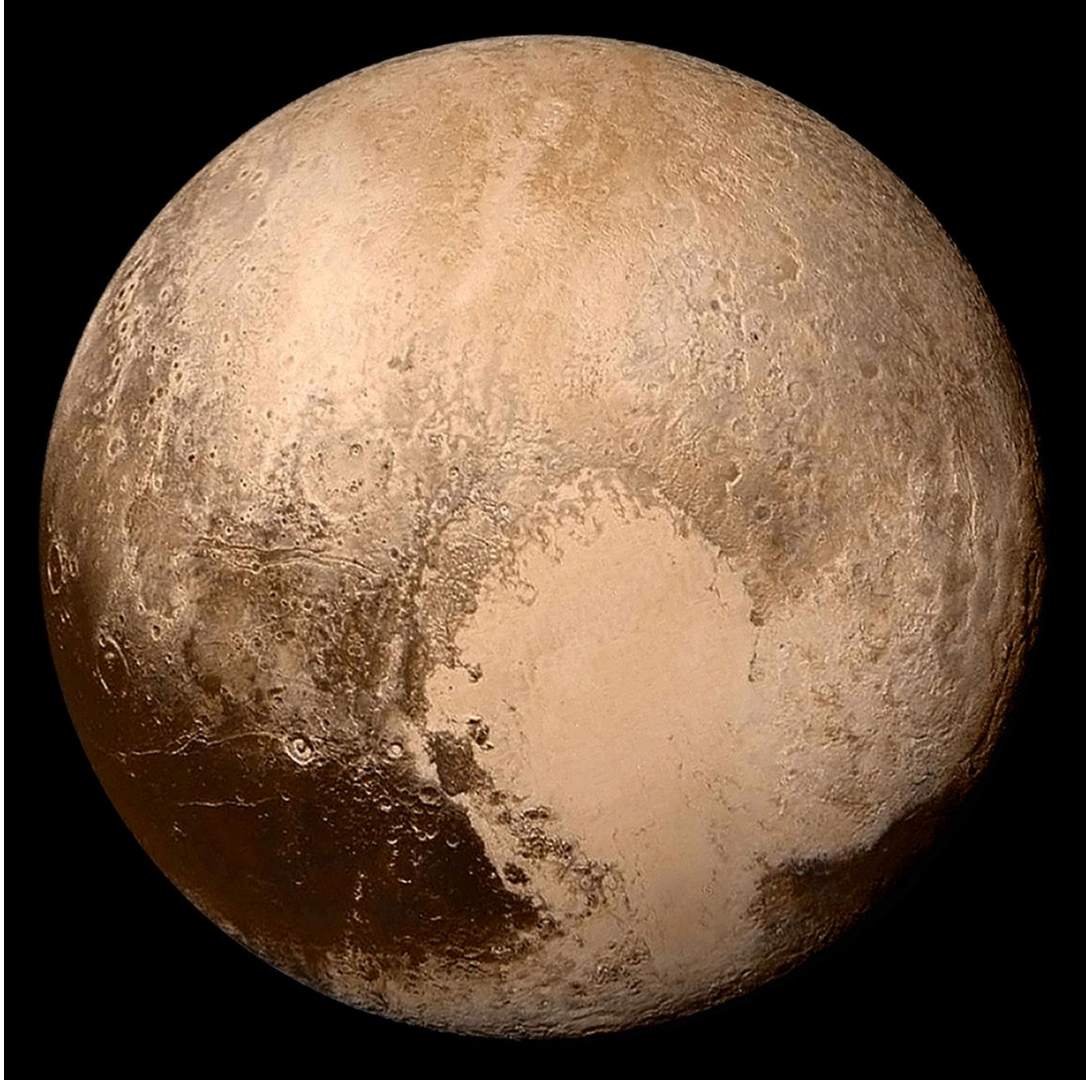
Planet	Venus	Mars
Escape process	Loss rate (s^{-1})	Loss rate (s^{-1})
Jeans: H	2.5×10^{19}	1.5×10^{26}
Photo-chemical reactions: H^*	3.8×10^{25}	
Photo-chemical reactions: O^*		2.8×10^{24}
Electric field force[a]: H^+	$\leqslant 7 \times 10^{25}$	
Ion pick up: H^+	1×10^{25}	1.2×10^{25}
Ion pick up: H_2^+	$< 10^{23}$	1.2×10^{25}
Pick up: O^+	1.6×10^{25}	3×10^{24}
Detached plasma clouds: O^+	5×10^{24}– 1×10^{25}	$\approx 1 \times 10^{24}$
Sputtering: O	6×10^{24}	2.2×10^{23}

[Lammer et al., PSS, 2006]

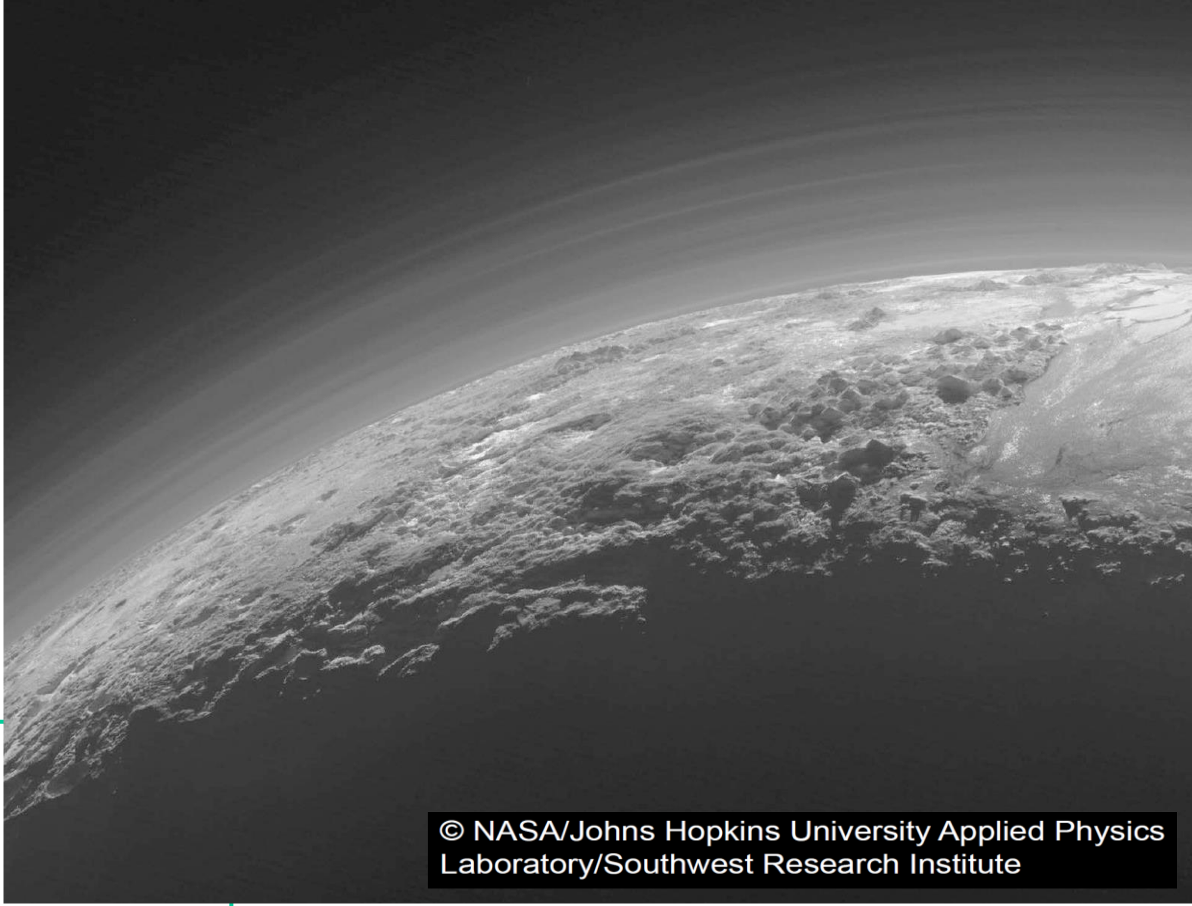
Pickup at Pluto

- New Horizons:
  Pluto flyby 14 July 2015





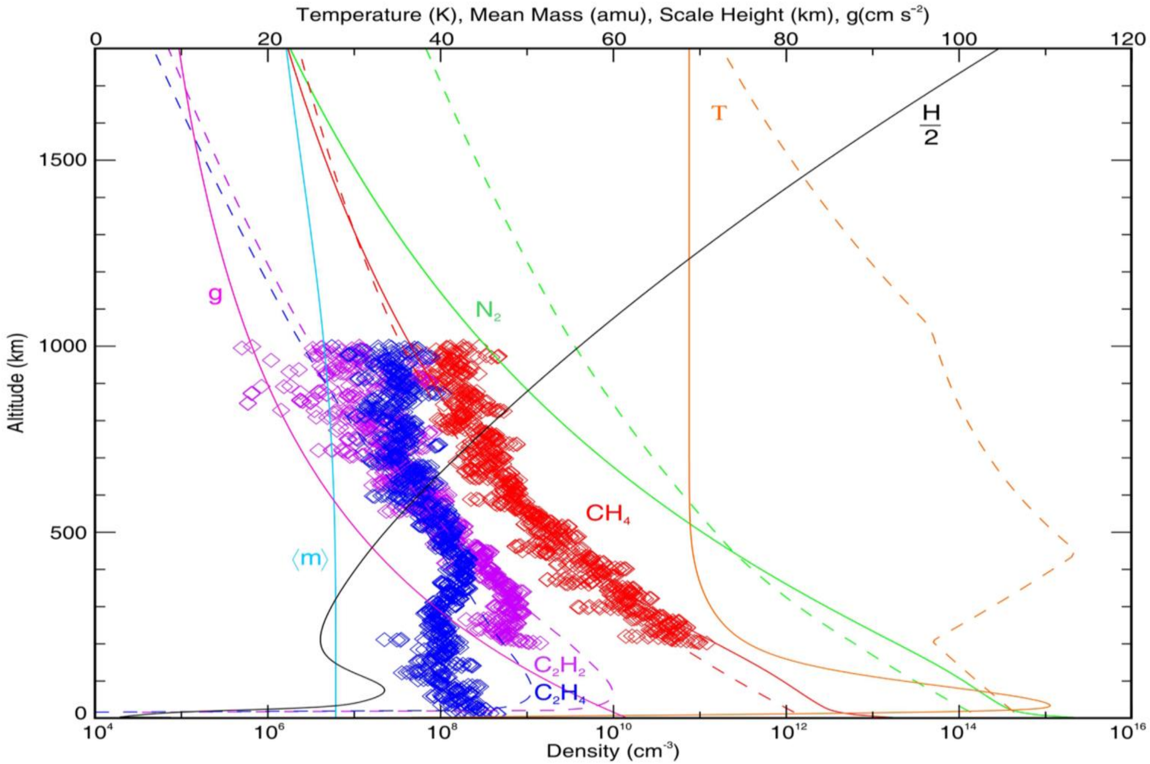
Pluto‘s atmosphere



© NASA/Johns Hopkins University Applied Physics Laboratory/Southwest Research Institute

- Tenuous atmosphere: N_2, CH_4
- Pressure: 1 Pa (10 µbar)
- Upper atmosphere extremely cold: 70 K
- $g = 0.6\ m/s^2$ (1/16 of Earth)
- $V_{escape} = 1.21\ km/s$

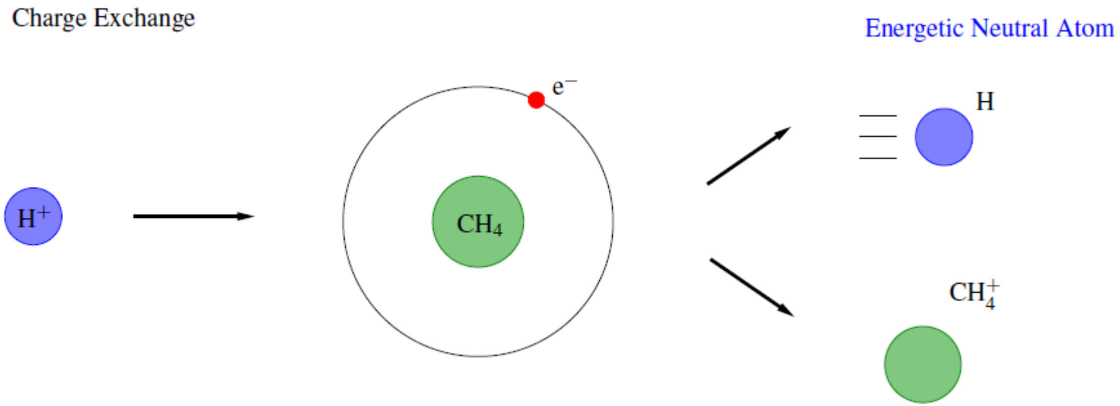
Pluto‘s atmosphere: neutral density profiles

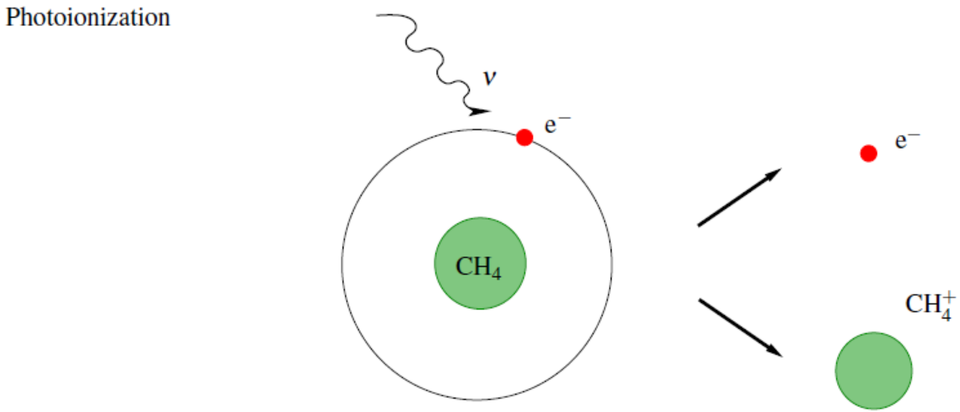


- Nitrogen, Methane as major components
- Ethine, Ethene as minor components

[Gladstone et al, Science, 2016]

Ionization of atmospheric molecules

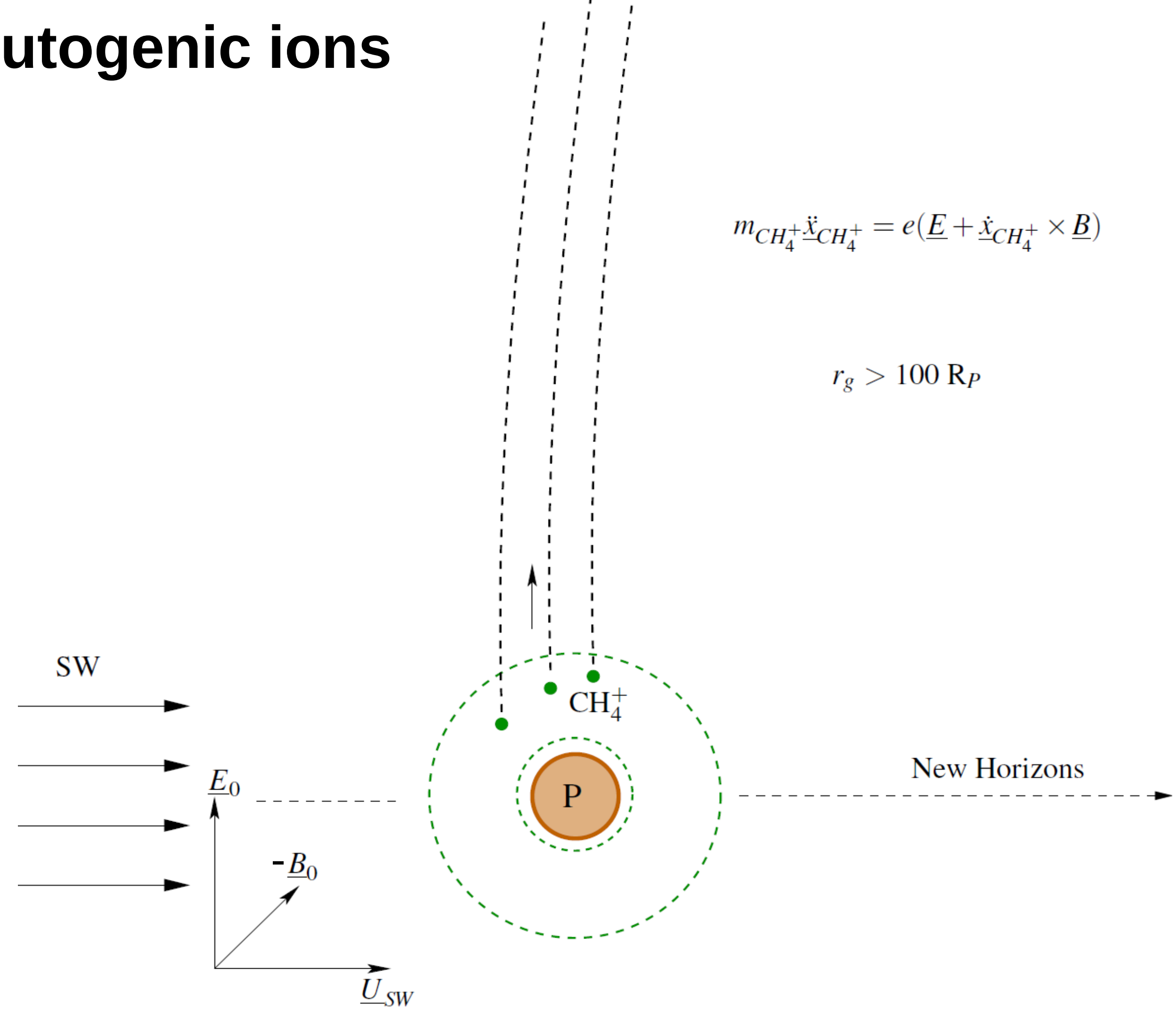

Charge Exchange


Photoionization

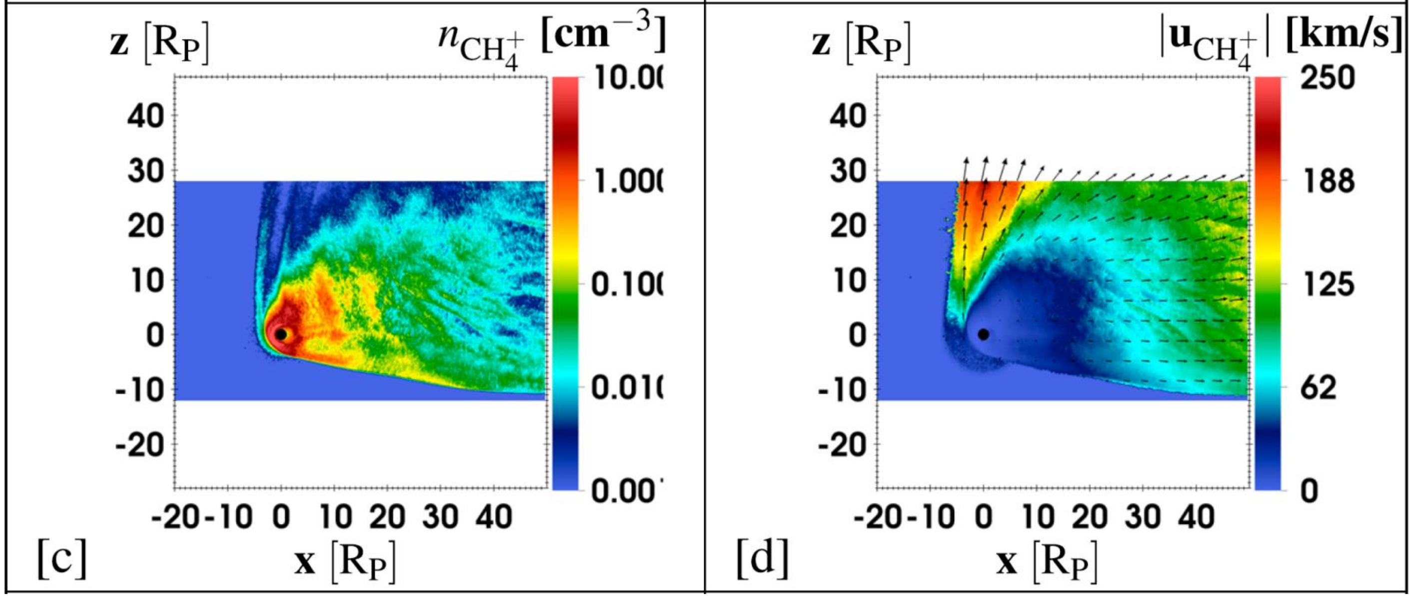
Pickup of newborn Plutogenic ions

$$m_{CH_4^+}\underline{\ddot{x}}_{CH_4^+} = e(\underline{E} + \underline{\dot{x}}_{CH_4^+} \times \underline{B})$$

$$r_g > 100 \text{ R}_P$$



Pickup of newborn Plutogenic ions



A.I.K.E.F.
Adaptive Ion Kinetic Electron Fluid Simulation Code

- CH_4^+: 3 10^{23} /s ~ 8 g/s
- N_2^+: 4 10^{24} /s ~ 187 g/s

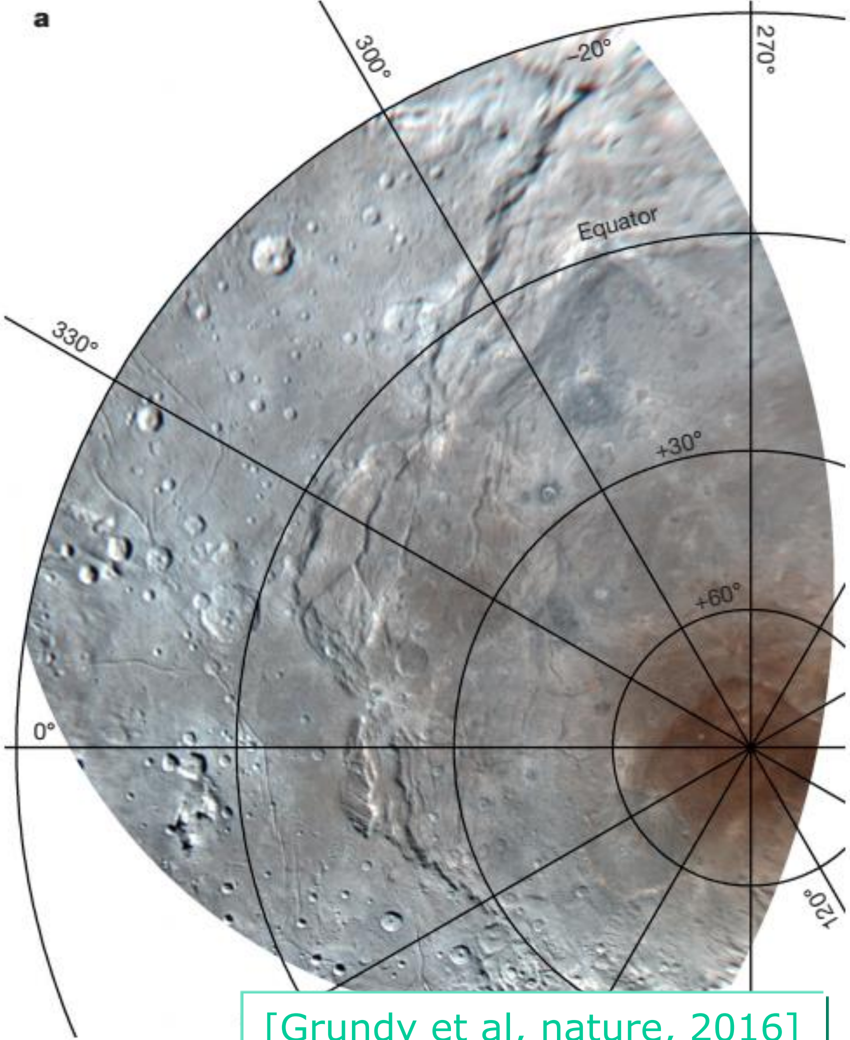
[Feyerabend et al, JGR, 2017]

Thermal escape

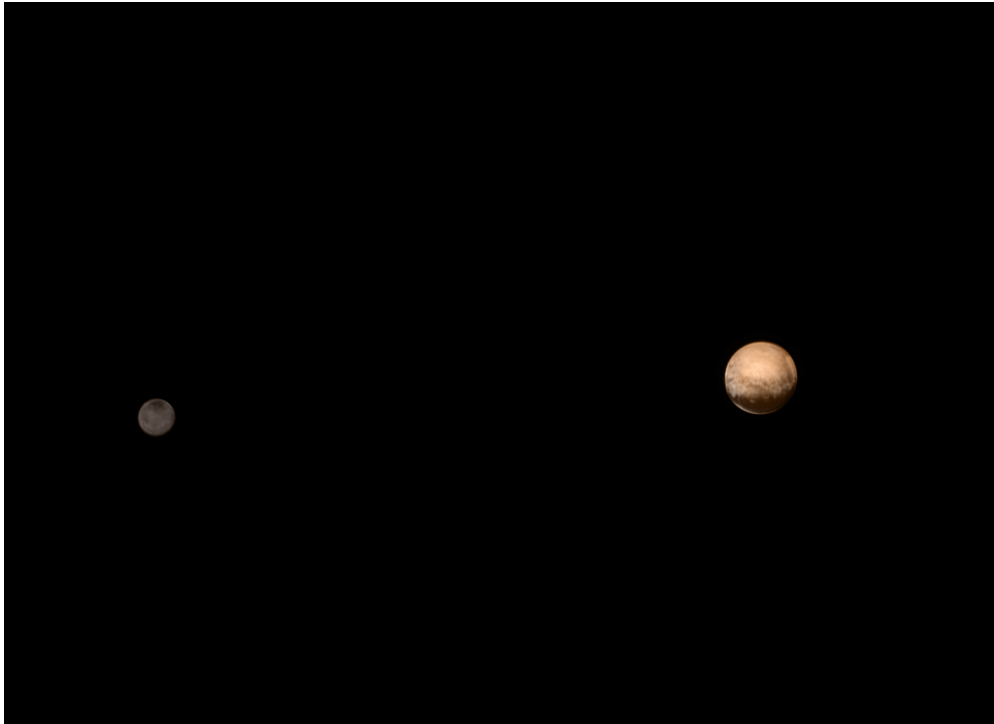
- CH_4: 5 10^{25} /s ~ 1.5 µm ice/Pyr → 28 m ss age
- N_2: 10^{23} /s ~ 3 nm ice/Pyr → 6 cm ss age

[Gladstone et al, Science, 2016]

Gas transfer from Pluto to Charon



[Grundy et al, nature, 2016]



http://pluto.jhuapl.edu/Multimedia/Science-Photos/image.php?gallery_id=2&image_id=20

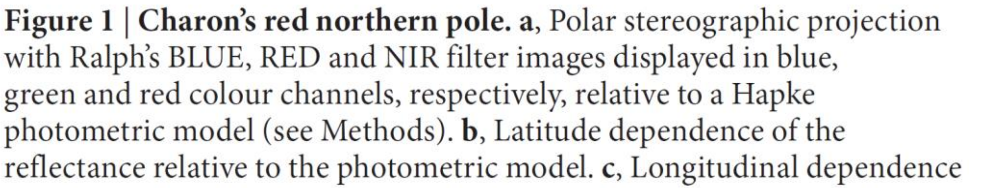


Figure 1 | Charon's red northern pole. a, Polar stereographic projection with Ralph's BLUE, RED and NIR filter images displayed in blue, green and red colour channels, respectively, relative to a Hapke photometric model (see Methods). **b**, Latitude dependence of the reflectance relative to the photometric model. **c**, Longitudinal dependence

Pickup at Titan

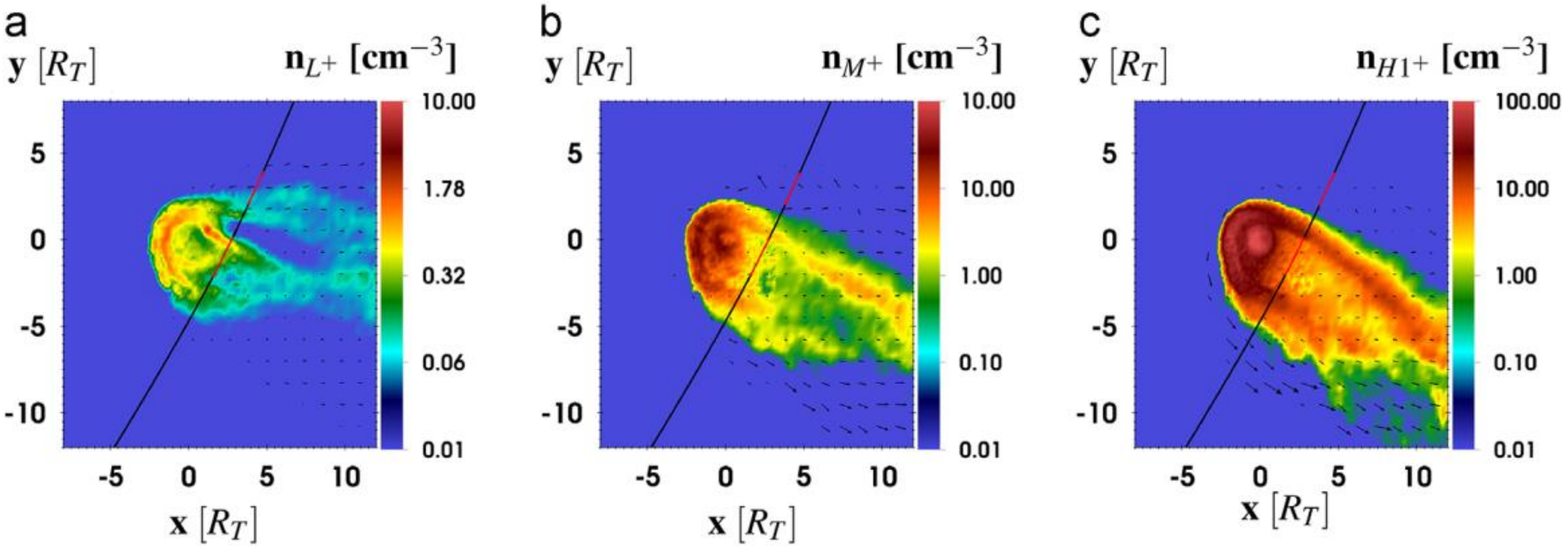


Fig. 10. Densities of the (a) L^+, (b) M^+ and (c) $H1^+$ species in the $z = 1.5\ R_T$ plane for T63. Arrows indicate velocities of the respective ion species. The black line shows the T63-trajectory, with the intervals of the observed split signatures marked in red. Cassini moved from $y > 0$ towards $y < 0$ during T63. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

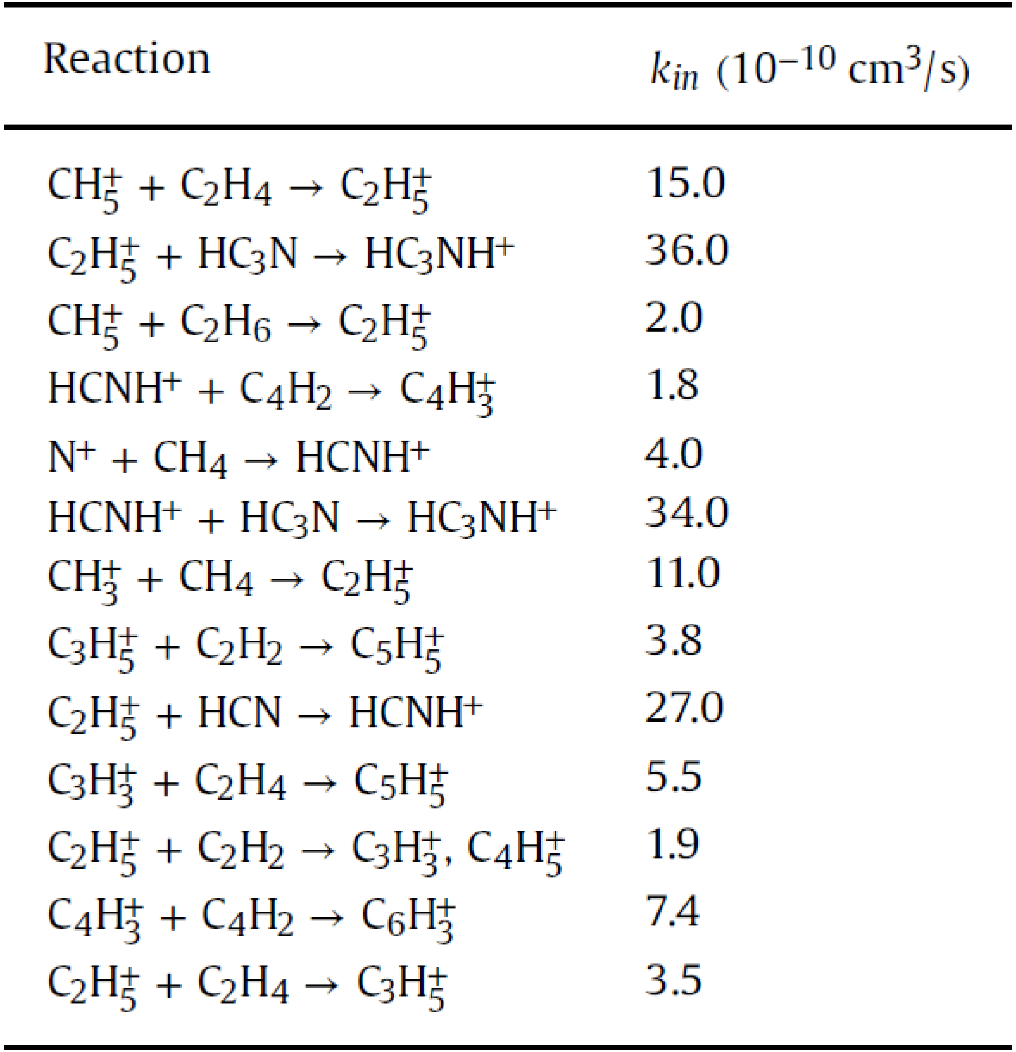
- N_2^+: 3 10^{26} /s ~ 14 kg/s
- CH_4^+: 6 10^{24} /s ~ 160 g/s
- H_2^+: 3 10^{23} /s ~ 1 g/s

- H_2: 10^{28} /s (thermal loss [Strobel & Cui, 2014])

[Feyerabend et al, PSS, 2015]

Chemical Escape

Species may be lost
by chemical reaction



Reaction	k_{in} $(10^{-10}\ \mathrm{cm^3/s})$
$CH_5^+ + C_2H_4 \rightarrow C_2H_5^+$	15.0
$C_2H_5^+ + HC_3N \rightarrow HC_3NH^+$	36.0
$CH_5^+ + C_2H_6 \rightarrow C_2H_5^+$	2.0
$HCNH^+ + C_4H_2 \rightarrow C_4H_3^+$	1.8
$N^+ + CH_4 \rightarrow HCNH^+$	4.0
$HCNH^+ + HC_3N \rightarrow HC_3NH^+$	34.0
$CH_3^+ + CH_4 \rightarrow C_2H_5^+$	11.0
$C_3H_5^+ + C_2H_2 \rightarrow C_5H_5^+$	3.8
$C_2H_5^+ + HCN \rightarrow HCNH^+$	27.0
$C_3H_3^+ + C_2H_4 \rightarrow C_5H_5^+$	5.5
$C_2H_5^+ + C_2H_2 \rightarrow C_3H_3^+, C_4H_5^+$	1.9
$C_4H_3^+ + C_4H_2 \rightarrow C_6H_3^+$	7.4
$C_2H_5^+ + C_2H_4 \rightarrow C_3H_5^+$	3.5

Example:
Chemical processes
in Titan‘s atmosphere

[Feyerabend et al, PSS, 2015]

Summary

- Atmospheres of planetary bodies may be lost by thermal or non-thermal escape
- Atmospheres of planets and moons in solar system are hydrodynamically stable
- Hydrodynamically unstable atmospheres at comets, hot jupiters
- Pickup as major non-thermal loss process for unprotected atmospheres
- Pickup in competition to Jeans escape for heavy species
- Atomic hydrogen lost mainly by Jeans escape
- General conclusions are difficult because of diversity of atmospheres