PG lecture: planetary upper atmospheres

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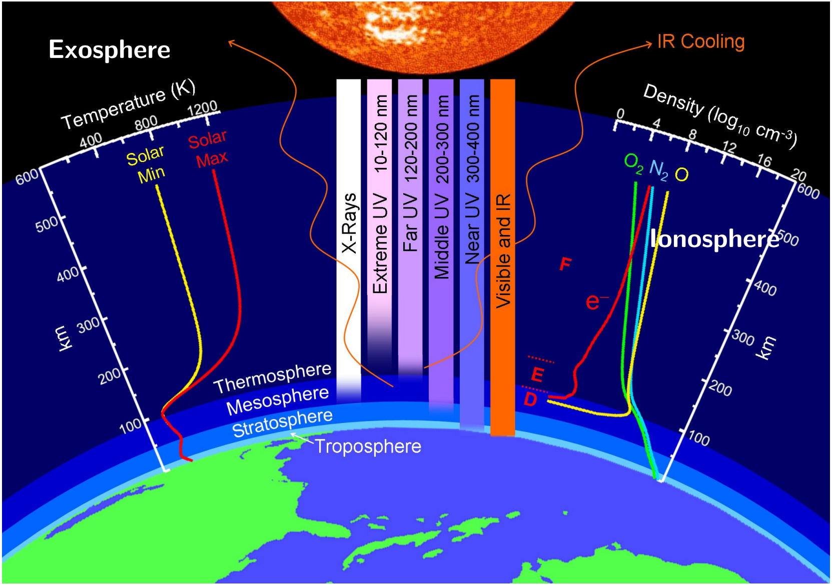
November 14th, 2017

Today

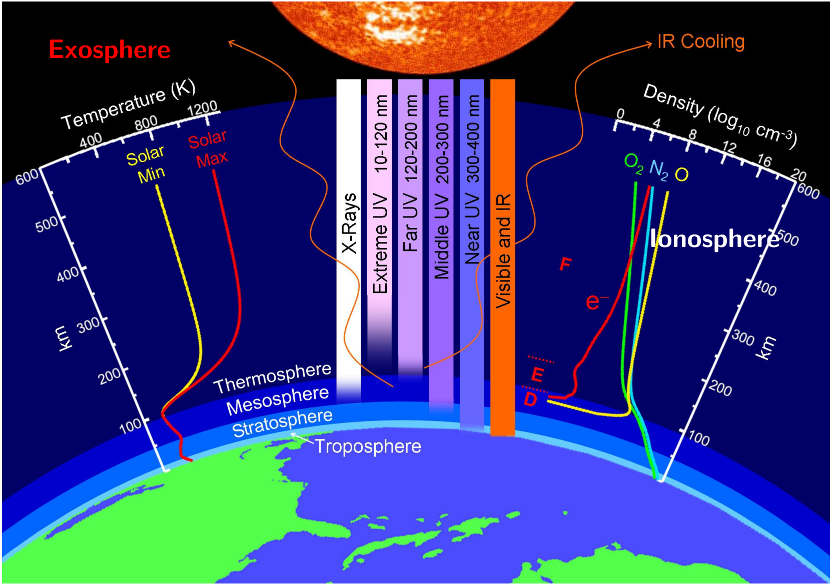
- *Explore* two layers of the atmosphere
- *Characterise* each of them
- *Understand* the physics and the chemistry involved
- *How to model*

Overview of Earth upper atmosphere



Credits: NASA

What is the exosphere?



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A border: the exobase

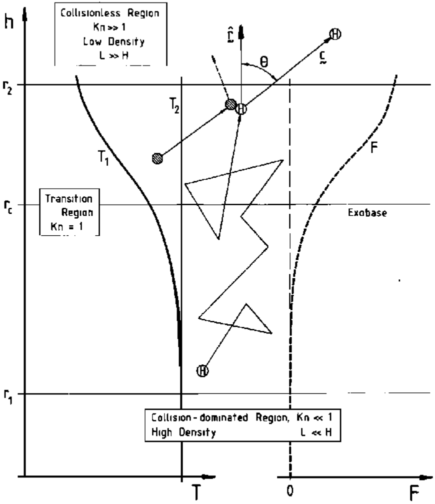

Figure: Fahr and Shizgal, 1983

- The exobase is a characteristic limit
- $\lambda = (n\sigma)^{-1}$ the mean free path is the same order as the scale height $H = k_B T / mg$
- Above, dynamics of individual particles is dominated by external forces
- Below, collisions prevent light particles to escape
- The gas is no longer in thermodynamic equilibrium

Surface-bounded exosphere

If the atmosphere is not dense enough, the exobase is the surface: Mercury or Ganymede

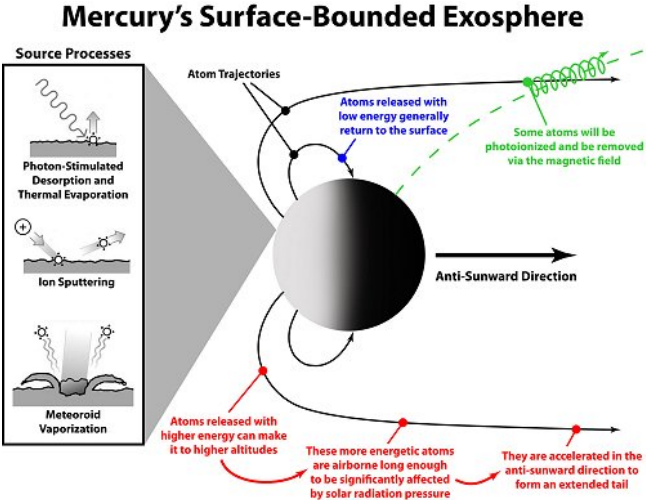

Figure: Credits: NASA

The limit of the fluid description

The conditions for the fluid approach are not completely fulfilled within the exosphere.

The gas cannot be described by macroscopic quantities such as pressure, temperature, etc...

$\longrightarrow$ How to take that into account?

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Distribution function

f number density in position [m^{-3}] and velocity [m^{-3}.s^{3}]
$\longrightarrow$ $[f]$ =[m^{-6}.s^{3}]

Particles behaviour is described by a distribution function f:
the probability to have a particle around the velocity (v_x, v_y, v_z) at the position $\vec{r}$

For example, the number N of particles around the velocity (v_x, v_y, v_z) and position (x, y, z) is given by

$$N(x, y, z) = f(\vec{r}, v_x, v_y, v_z)\Delta v_x \Delta v_y \Delta v_z \Delta x \Delta y \Delta z$$

The number density

$$n(x, y, z) = N/(\Delta x \Delta y \Delta z)$$

For example, the total local density n_0 is given by

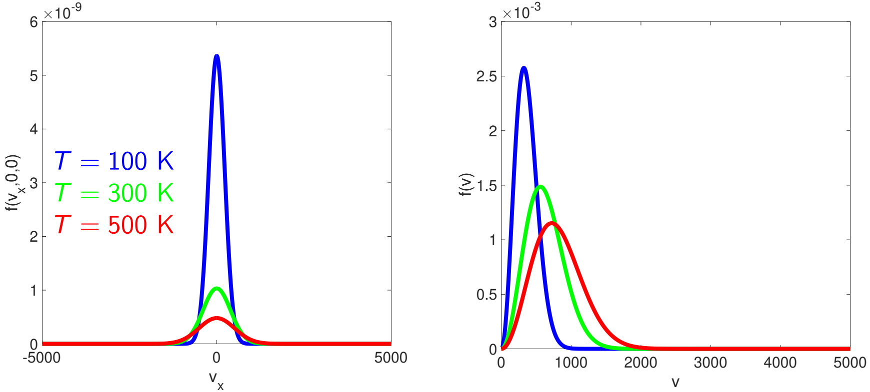
$$n_0(\vec{r}) = \int f(\vec{r}, v_x, v_y, v_z)\, \mathrm{d}v_x\, \mathrm{d}v_y\, \mathrm{d}v_z$$

Thermodynamical equilibrium

The gas obeys to a maxwellian distribution:

$$f(v_x, v_y, v_z) = \frac{n_0}{\pi^{3/2} v_{th}^3} \exp\left(-\frac{mv_x^2}{2k_B T}\right) \exp\left(-\frac{mv_y^2}{2k_B T}\right) \exp\left(-\frac{mv_z^2}{2k_B T}\right)$$

$$f(v) = n_0 \sqrt{\frac{16}{\pi}} \frac{v^2}{v_{th}^3} \exp\left(-\frac{mv^2}{2k_B T}\right), \quad v_{th} = \sqrt{\frac{2k_B T}{m}}$$



And for non-thermodynamical equilibrium? Time-dependent?

Need an equation to rule them all: the Boltzmann equation

$$\frac{\partial f}{\partial t} + \nabla_{\vec{r}} \cdot (f\vec{v}) + \nabla_{\vec{v}} \cdot (f\vec{a}) = \left(\frac{\partial f}{\partial t}\right)_{collisions}$$

If the forces are conservative:

$$\frac{\partial f}{\partial t} + \underbrace{v_x\frac{\partial f}{\partial x} + v_y\frac{\partial f}{\partial y} + v_z\frac{\partial f}{\partial z}}_{\text{advection in position}} + \underbrace{a_x\frac{\partial f}{\partial v_x} + a_y\frac{\partial f}{\partial v_y} + a_z\frac{\partial f}{\partial v_z}}_{\text{advection in velocity}} = \left(\frac{\delta f}{\delta t}\right)_{collisions}$$

$\left(\frac{\delta f}{\delta t}\right)_{collisions}$ contains the collisions, the source and loss terms.

Processes dominating the upper atmosphere

- Elastic collisions: like collisions between 2 hard spheres

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Depends on the cross-section, function of the relative velocity between species.

Forces present in the exosphere

- Gravity (for cold neutrals)

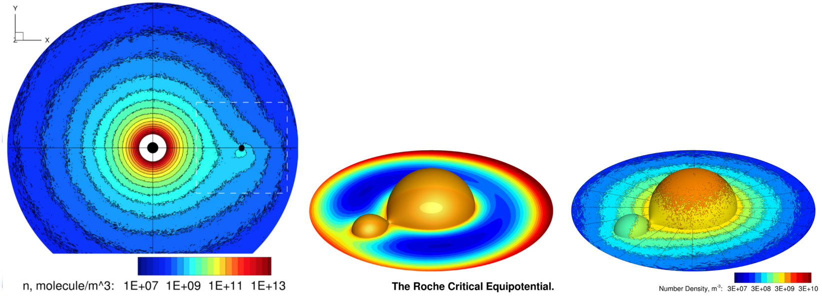

Figure: Hoey et al., 2016

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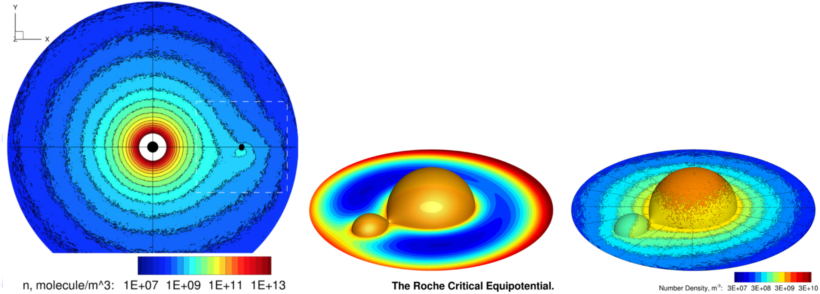

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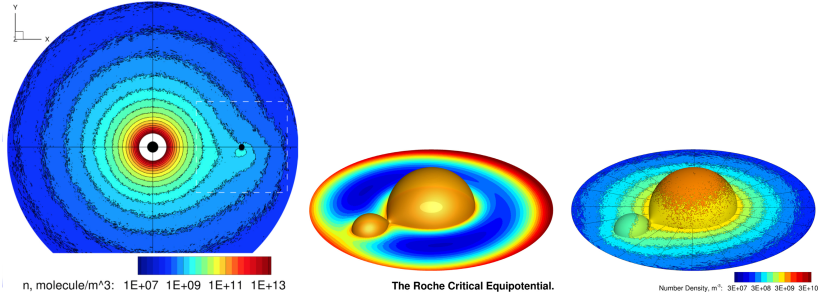

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- Radiation pressure (for Hydrogen)
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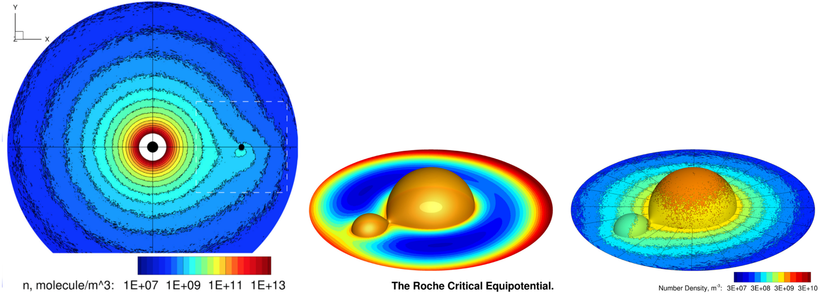


Figure: Hoey et al., 2016

- Radiation pressure (for Hydrogen)
- Magnetic field (for ions and electrons)
- Electric ambipolar field (to ensure plasma quasi-neutrality)

Thermal escape

Species are naturally leaving the planet at different rates, especially the light ones

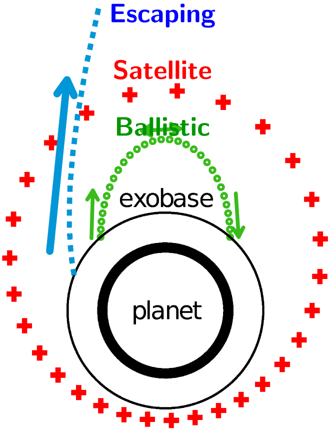
⟶ Thermal escape

⟶ It corresponds to the flux of particles with a velocity higher than the escape velocity at the exobase

$$F = \int_{v_{esc}}^{+\infty} v f(v) \mathrm{d}v, \text{ with } \; v_{esc} = \sqrt{\frac{2GM}{r_{exo}}}$$

⟶ Not efficient for heavy species, other mechanisms are involved to remove the atmosphere from the planet

Case study: no collisions and gravity



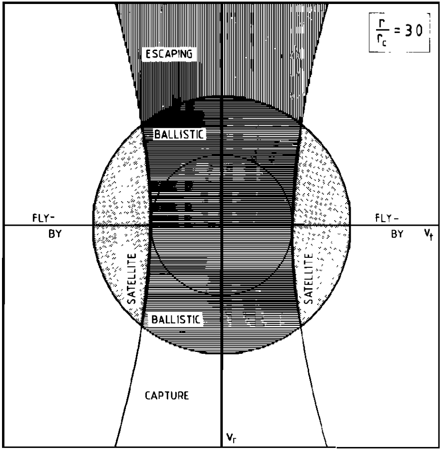
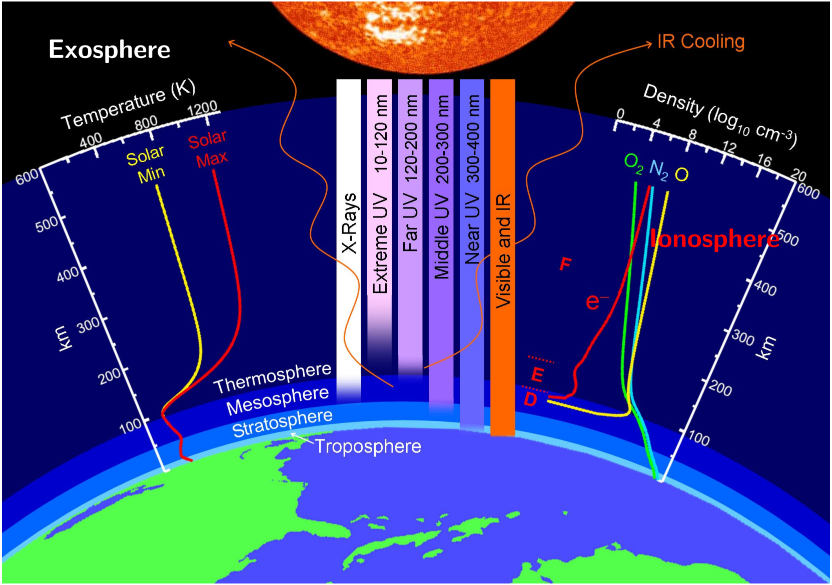


Figure: Fahr and Shizgal, 1983

Take home messages: exosphere

- Tenuous part of the neutral atmosphere
- Few collisions
- Region of interaction with the interplanetary medium
- Easy for particles to escape into the planetary medium
- Dynamics dominated by external forces and a few collisions
- Directly bounded at the surface for some cases

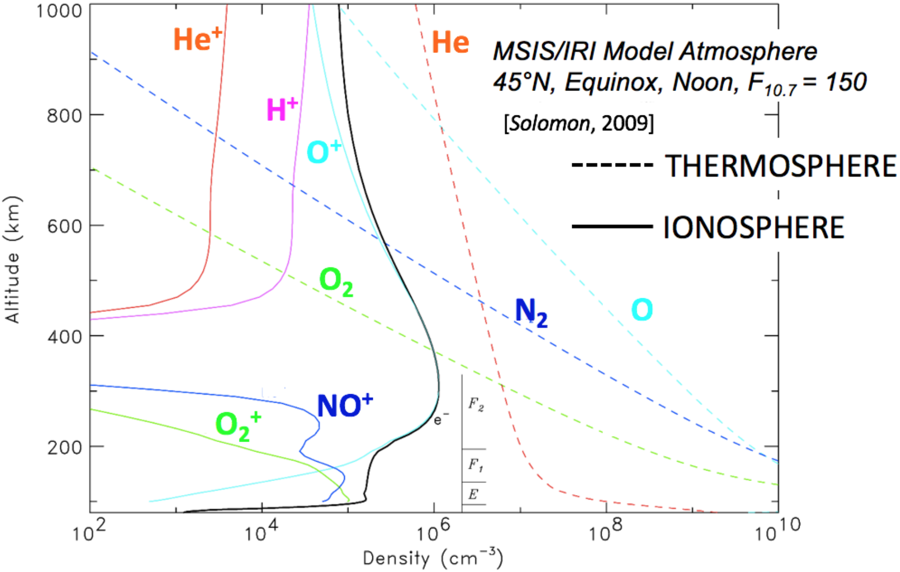
What is the ionosphere?



What is the ionosphere?

- Layer of cold (< 1 eV) plasma (free e^- and ions) embedded in a neutral envelope of gas around planets, moons, and comets.
- Formed by ionization of neutral atoms and molecules through:
  -Absorption of solar XUV radiation (0.1 – 100 nm)
  -Collisions with energetic particles (e.g., magnetospheric or solar origin)
- In dense atmospheres: located in the outer layers
- In thin atmospheres: located in the whole exosphere or coma down to the surface
- Composition of the ionosphere is controlled by the neutral gas composition
- Dynamics affected by ambient magnetic fields, if present.

Ionospheric composition at Earth



Day/night and solar activity variability

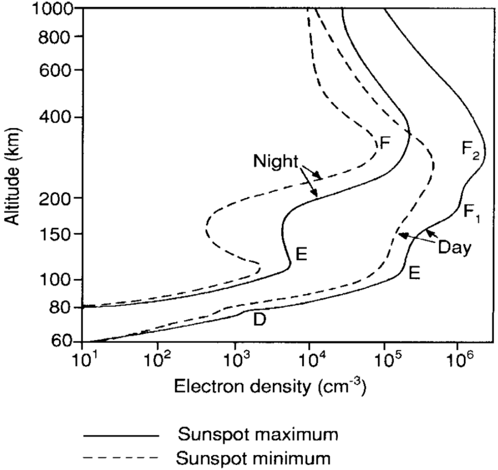


Figure: After W. Swider, Wallchart Aerospace Environment, US Air Force Geophysics Laboratory (see Hargreaves 1992)

Importance of the ionosphere

Ionosphere allows to close the magnetospheric current system, strong coupling

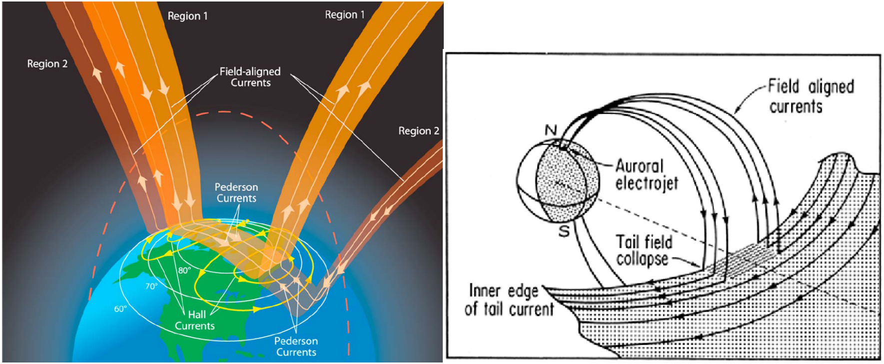
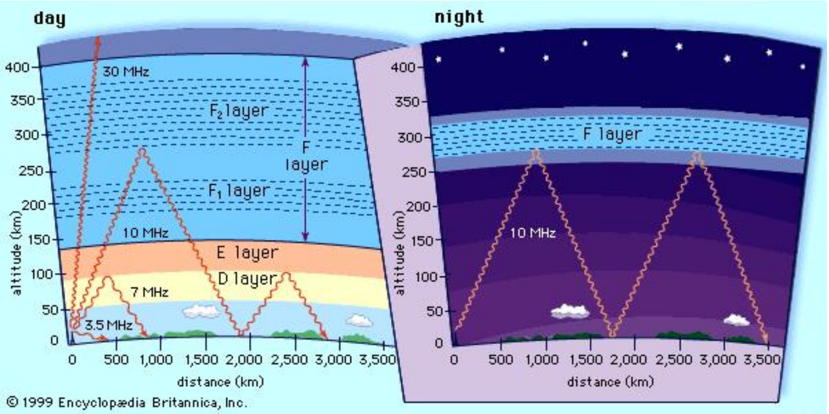


Figure: From wikipedia and McPherron et al. 1973

Radio communication

Ionosphere reflects radio waves. The altitude at which waves are reflected depends on the electron number density.



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⟶ The ionosphere can be probed by radio waves

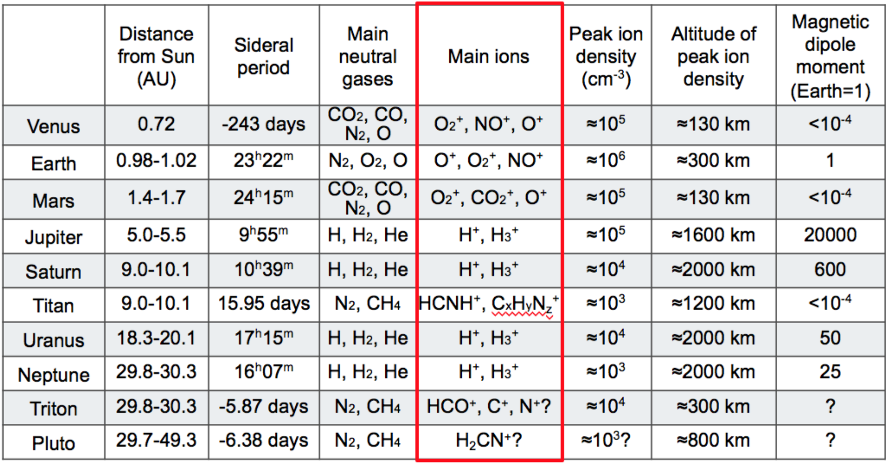
Space weather implications

Strong variations of the ionospheric currents during space weather events

Increase of the Joule heating efficiency
⟶ Heating of the atmosphere
⟶ The atmosphere expands

Induce current at the ground
⟶ Geomagnetically induced currents (GIC)
⟶ Electrical disruption

Ionospheric composition



	Distance from Sun (AU)	Sideral period	Main neutral gases	Main ions	Peak ion density (cm^{-3})	Altitude of peak ion density	Magnetic dipole moment (Earth=1)
Venus	0.72	-243 days	CO_2, CO, N_2, O	O_2^+, NO^+, O^+	≈10^5	≈130 km	<10^{-4}
Earth	0.98-1.02	23^h22^m	N_2, O_2, O	O^+, O_2^+, NO^+	≈10^6	≈300 km	1
Mars	1.4-1.7	24^h15^m	CO_2, CO, N_2, O	O_2^+, CO_2^+, O^+	≈10^5	≈130 km	<10^{-4}
Jupiter	5.0-5.5	9^h55^m	H, H_2, He	H^+, H_3^+	≈10^5	≈1600 km	20000
Saturn	9.0-10.1	10^h39^m	H, H_2, He	H^+, H_3^+	≈10^4	≈2000 km	600
Titan	9.0-10.1	15.95 days	N_2, CH_4	$HCNH^+$, $C_xH_yN_z^+$	≈10^3	≈1200 km	<10^{-4}
Uranus	18.3-20.1	17^h15^m	H, H_2, He	H^+, H_3^+	≈10^4	≈2000 km	50
Neptune	29.8-30.3	16^h07^m	H, H_2, He	H^+, H_3^+	≈10^3	≈2000 km	25
Triton	29.8-30.3	-5.87 days	N_2, CH_4	HCO^+, C^+, N^+?	≈10^4	≈300 km	?
Pluto	29.7-49.3	-6.38 days	N_2, CH_4	H_2CN^+?	≈10^3?	≈800 km	?

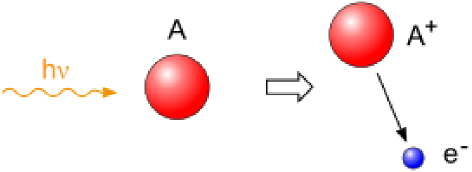
(Adapted from Müller-Wodarg 2004)

Depends on the neutral composition, the chemistry, the solar radiation, ...

Dominant production processes in the ionosphere

- Photo-ionisation: production of energetic photo-electron

$$E(e^-) = h\nu - E_{\text{ionisation}}$$



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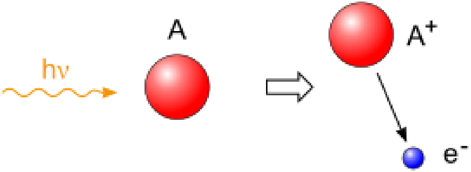
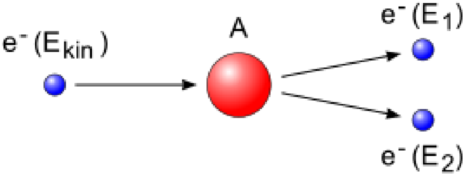


- e$^-$-impact ionisation:

$$E(e^-) = E_1 + E_2 - E_{\text{ionisation}}$$

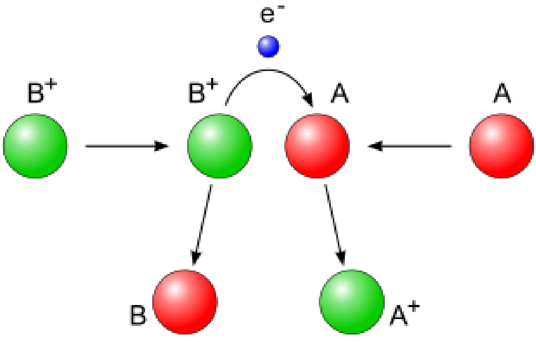


from https://lp.uni-goettingen.de/

Most of the input energy (photon or electron kinetic energy) is transferred to the particle with the lower mass, the electron.

Dominant production/loss processes in the ionosphere

- Charge transfer



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Do not change the plasma density

Solar energy absorption vs altitude

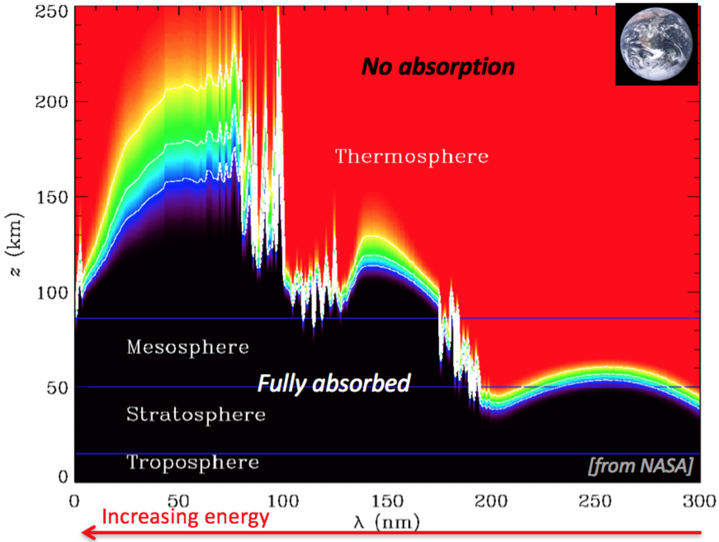
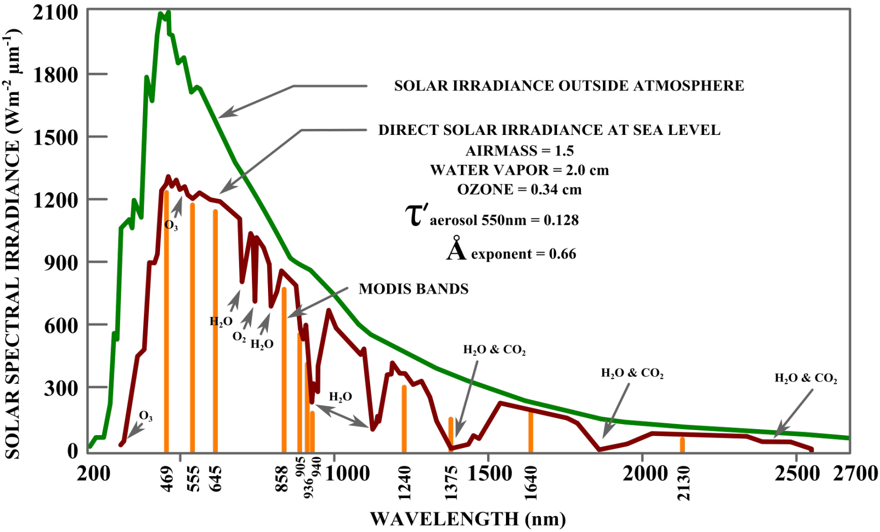


Figure: Altitude of penetration of solar UV radiation for an overhead Sun as a function of altitude

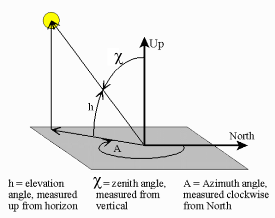
EUV strongly absorbed by species for photoionisation

Solar energy absorption vs altitude



Solar attenuation: Beer Lambert law

Plane parallel approximation



$$I(\lambda, z) = I(\lambda, \infty) \exp\left(\underbrace{-\sum_i \sigma_i(\lambda) \int_z^{+\infty} n_i(z') \frac{\mathrm{d}z'}{\cos\chi}}_{\tau\ =\text{optical depth}} \right)$$

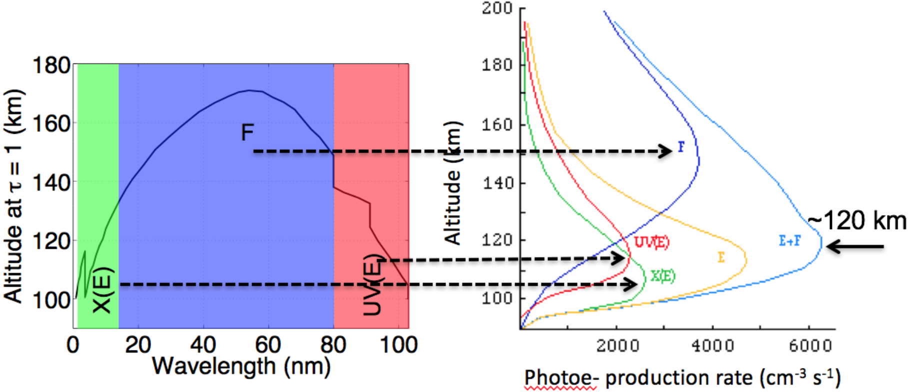
$I(\lambda, \infty)$ incident radiation at the top of the atmosphere
χ: zenith angle
σ_i: total photo-absorption cross-section for the species i

$$P_{e^-}(z, E) = \sum \sigma_{\text{ion}}(\lambda) n_i(z) I(\lambda, z)$$

σ_{ion}: total photo-ionisation cross-section for the species i
with $E = \dfrac{hc}{\lambda} - E_{\text{ion}}$
⟶ you do not produce electrons with the same energy

Energy absorption vs altitude

The maximum energy deposition occurs at $\tau(\lambda) = 1$.



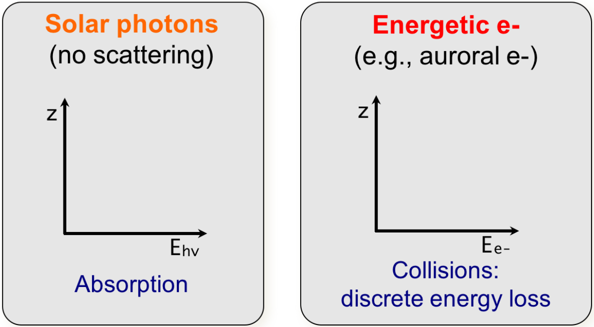
Energy vs altitude

Solar photons keep their energy but are more and more absorbed by the atmosphere

Electrons loose their energy through collisions

⟶ Electrons cool down (or loose energy) efficiently in the lower part of the ionosphere

⟶ Two electron populations can coexist: one hot and one cold population



Solar photons
(no scattering)

Absorption

Energetic e-
(e.g., auroral e-)

Collisions:
discrete energy loss

Beer-Lambert Law
(Radiative transfer equation)

Boltzmann equation

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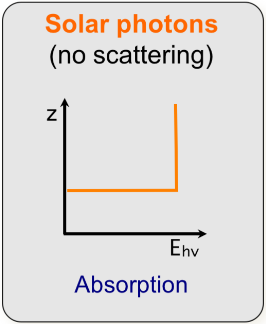

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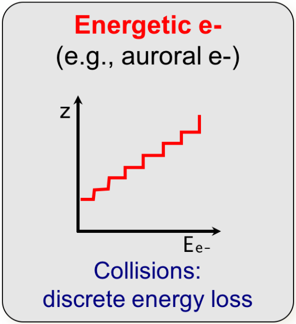

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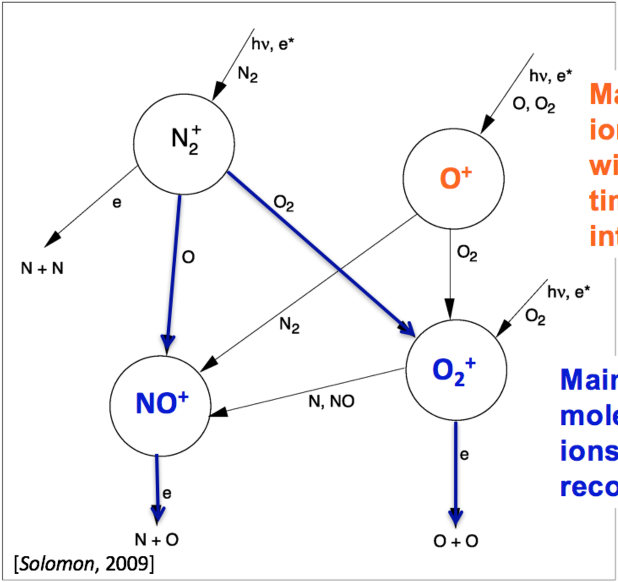
Ion loss processes at Earth



[*Solomon*, 2009]

Main loss of atomic ions (slow compared with transport timescale): ion-atom interchange

Main loss of molecular, terminal ions: dissociative recombination (DR)

Dominant forces

- Gravity
- Ambipolar field (see sketch)
- Magnetic field

Take home message: ionosphere

- Ionospheres exist around every planet, moon, comet with an atmosphere:
  - Formed by the ionisation of atmospheric neutrals
  - Result from the absorption of solar XUV radiation and energy deposition of particles from the space environment.
  - Ionospheric composition depends on the composition of the neutral, background atmosphere.
- Planetary ionospheres are an essential link between the solar wind, magnetosphere, and atmosphere:
  - Implication on space weather at Earth and beyond
  - Implication for global, magnetospheric current systems
  - Magnetosphere-ionosphere coupling revealed through auroral emissions

Conclusions

- Not easy to model both regions, need kinetic approach
- The exosphere is poorly characterised because of its tenuity
- The atmosphere can escape via the exosphere: evolution through years of the composition and density
- The ionosphere is sensitive to the solar activity.
- Comparative planetology aspect: any planet, comet, satellite has a ionosphere and an exosphere
  $\longrightarrow$Comparison of the evolution between the different bodies of the Solar System

Open questions

- Hot jupiters:
  What are the drivers of the dynamics and the shape of their exosphere?
- Comets:
  How does the cometary-solar wind interaction and ionospheric composition evolve with heliocentric distance? What is the contribution of ionospheric chemistry to the presence of complex organics in the coma?
- Ganymede:
  How does Ganymede's intrinsic magnetic field influence the plasma environment? How does it influence the detection of a subsurface ocean?