Influence of the radiation pressure on the planetary exospheres: density profiles, escape flux and atmospheric stability

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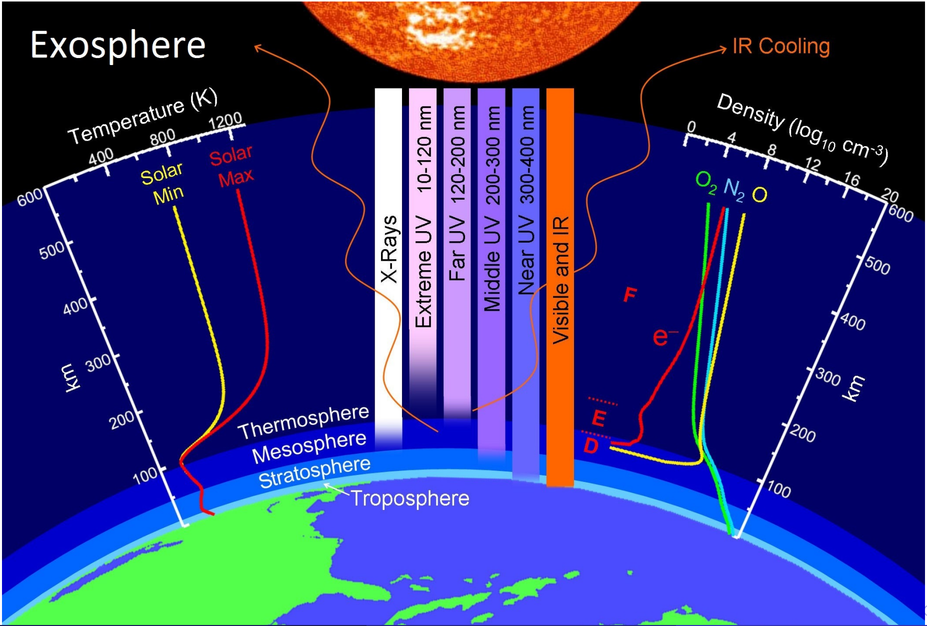
Outline

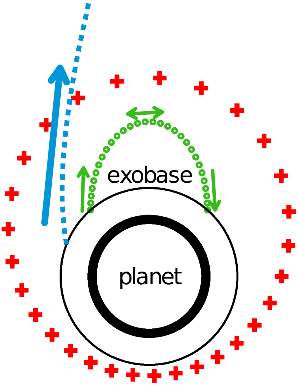
1. Context
2. Approach and formalism
3. Density profiles and escape flux
4. Implication on stability of planetary atmospheres
5. Conclusions

Description of the exosphere



Types of exospheric particles

The trajectories of neutrals are determined by external forces such as gravitation, radiation pressure. With only gravity, the trajectories are conics :



- ballistic : describing ellipses crossing the exobase
- satellite : describing ellipses **not** crossing the exobase
- escaping : coming from the exobase going to infinity

Chamberlain (1963) formalism

Chamberlain (1963) proposed an analytical formula to estimate the exospheric density and the contribution of each population

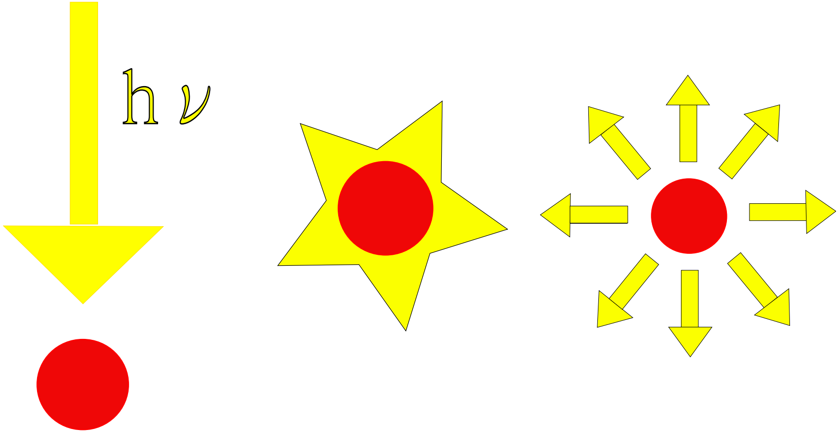
$$n(r) = n_{bar}\zeta(\lambda) = n(r_{exo})e^{\lambda-\lambda_{exo}}(\zeta_{bal} + \zeta_{esc} + \zeta_{sat})$$

$$\lambda(r) = \frac{GMm}{k_B T_{exo} r} = \frac{\text{gravitationnal energy}}{\text{thermal energy}}$$

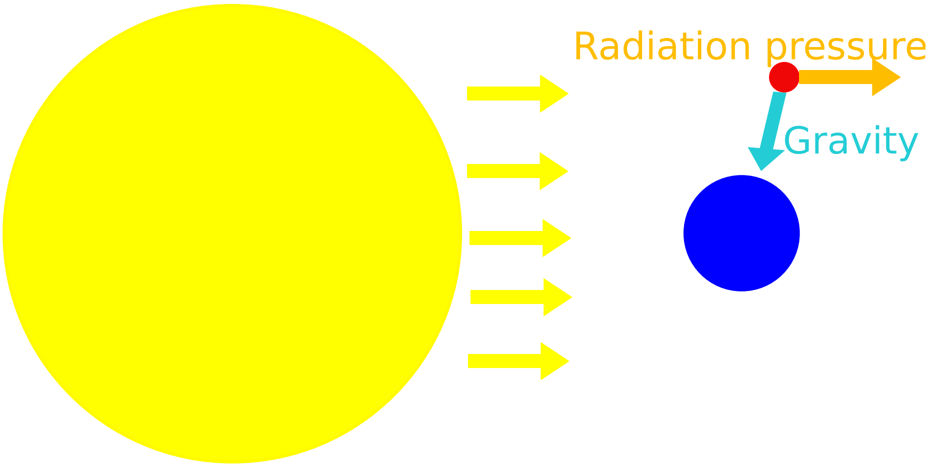
The ballistic particles are the main contribution near the planet.

The radiation pressure principle

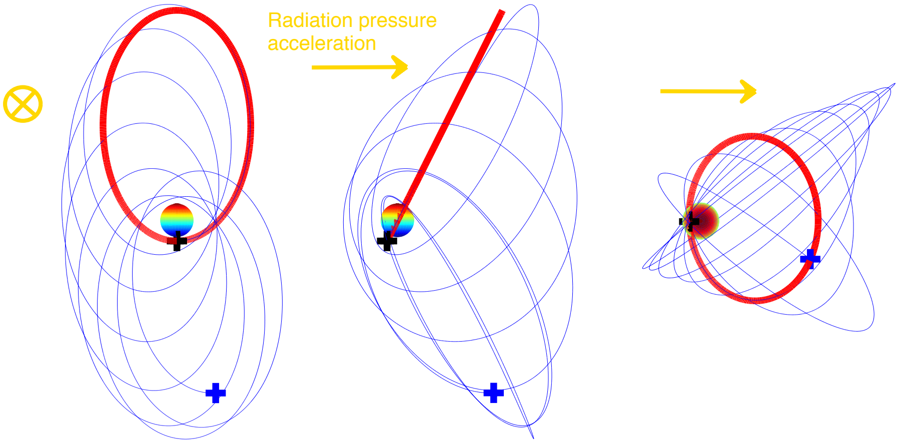
absorption excitation emission



Additional radiation pressure effect



Trajectory for an Hydrogen at Earth



Hamiltonian approach based on the Stark effect problem

$$\mathcal{H}(r,\theta,\phi,p_r,p_\theta,p_\phi,t) = \frac{p_r^2}{2m} + \frac{p_\theta^2}{2mr^2} + \frac{p_\phi^2}{2mr^2\sin^2\theta} - \frac{GMm}{r} + \underbrace{mar\cos\theta}_{\text{radiation pressure}}$$

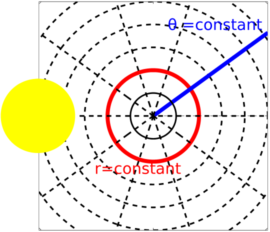


FIGURE: spherical frame

Change of frame

$\Longrightarrow$

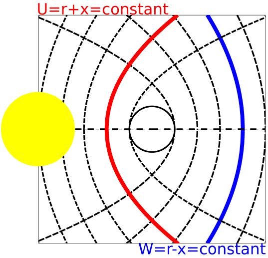


FIGURE: parabolic frame

$$\mathcal{H}(u,w,p_u,p_w,p_\phi) = \frac{2up_u^2 + 2wp_w^2}{m(u+w)} + \frac{p_\phi^2}{2muw} - \frac{2GMm}{u+w} + ma\frac{u-w}{2}$$

Topology of equipotentials

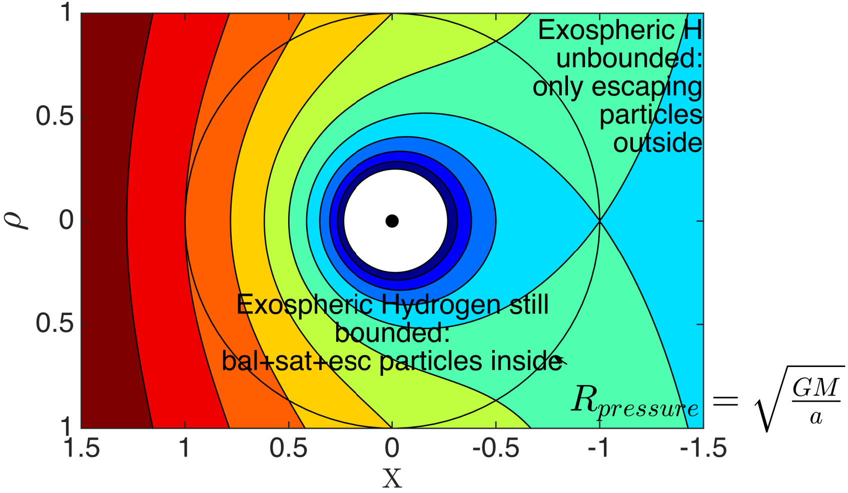


FIGURE: Equipotentials with the additional radiation pressure effect. Equipotentials are closed at finite distance, closed in the antisolar direction at $R_{pressure}$. N.B. : $\rho^2 = y^2 + z^2$, distances are given in units of $R_{pressure} = \sqrt{GM/a}$.

2D Ballistic particles density model (generalization of the 1D Chamberlain's one) with 2 parameters

$$n(r,\theta) = N_{exo}\exp(\lambda - \lambda_c)\exp\left(-\frac{ma}{k_B T}(r - r_{exo})\cos\theta\right) \times \zeta_{bal}(r,\theta)$$

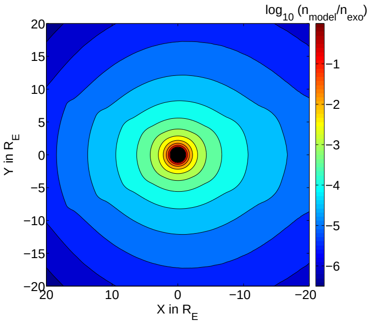


FIGURE: My model : equal density lines for H at Earth

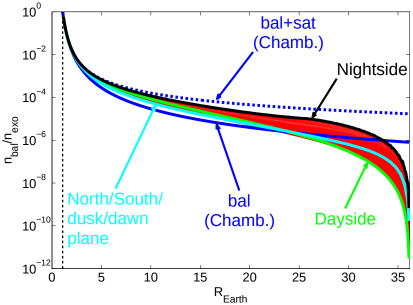
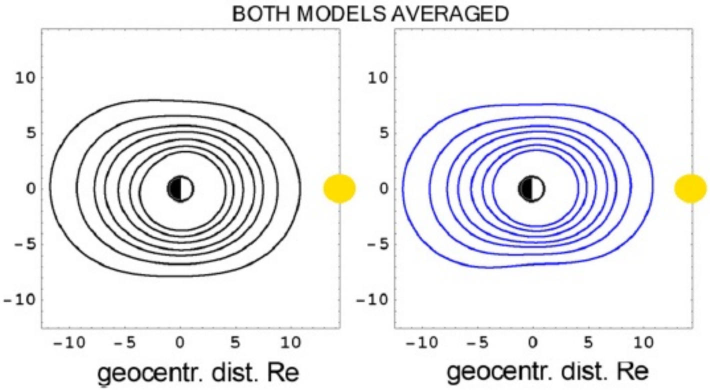


FIGURE: Radial density profiles depending on the direction at Earth

Comparison with observations at Earth (Zoennchen et al. 2013)



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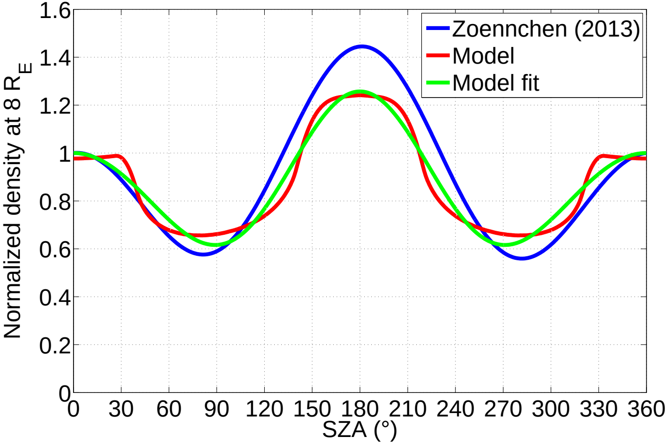
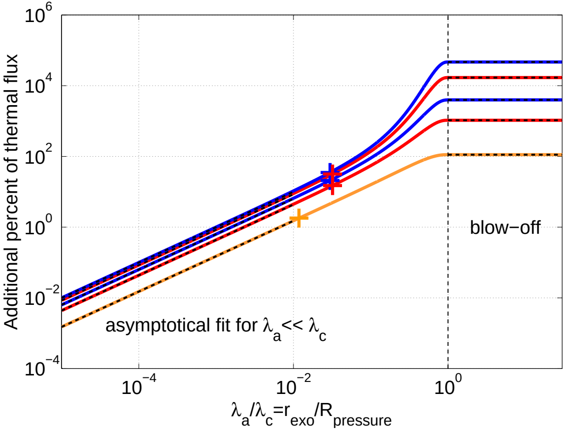


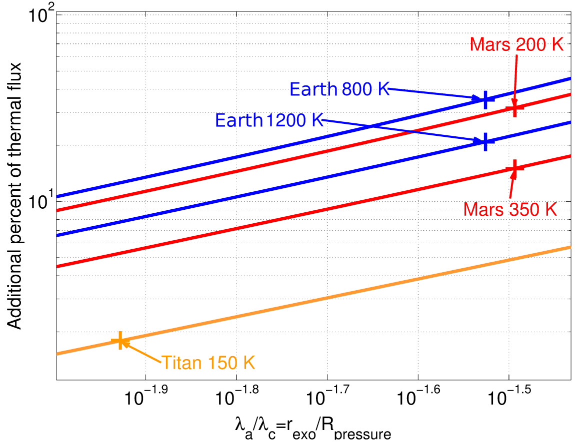
Agreement with observations : exospheric asymmetries well reproduced by the model.
Radiation pressure increases ballistic densities (e.g. $\times 4$ at 10 R_E)

Thermal escape flux modified by radiation pressure at the subsolar point



Increase of the thermal flux due to radiation pressure (vs Jeans' formula). The x-axis depends on $\sqrt{a}$. For $r_{exo} = R_{pressure}$, all particles at the exobase escape and we have a blow-off regime $\Longleftarrow$ Exospheric Hydrogen is not bounded any more

Thermal escape flux modified by radiation pressure at the subsolar point



Earth 20 – 35%

Mars 15 – 30%

Titan 1 – 2%

Three Body Problem + radiation pressure

Two additional external forces : **centrifugal force** and **stellar gravity**

What happens ? The potential becomes

$$\Omega(x,y,z) = \underbrace{\frac{1}{2}(x^2+y^2)}_{\text{centrifugal potential}} + \underbrace{\frac{\mu}{d_{planet}}}_{\text{planetary gravity}} +(1-\beta)\underbrace{\frac{1-\mu}{d_{star}}}_{\text{stellar gravity}}$$

$\beta = \dfrac{\text{radiation pressure}}{\text{stellar gravity}} \sim 0,5$ to 2 (Solar system) and higher (e.g. HD 209458b)

$$\mu = \frac{M_{planet}}{M_{Star} + M_{planet}}$$

$\Omega =$ constant gives equipotentials.

Sphere of gravitational influence modified by radiation pressure

Hill's sphere radius scaled by planet-star distance

$$3R_H^3 - \mu \approx 0 \Longrightarrow R_H = \sqrt[3]{\frac{\mu}{3}}$$

Derivation of a new Hill's sphere radius (R_H) taking into account the radiation pressure given by

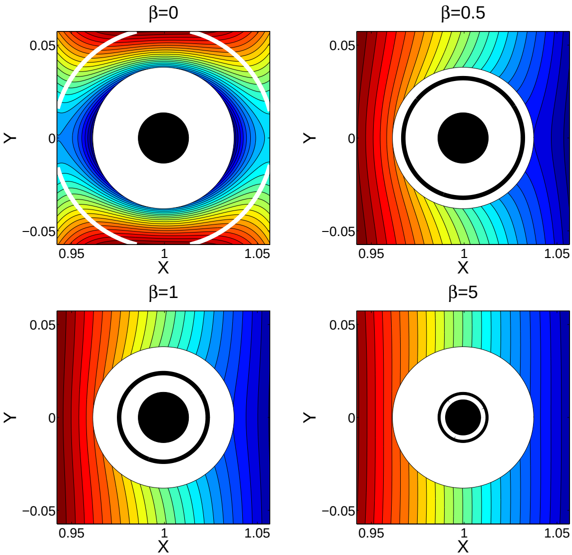
$$3R_H^3 + \beta R_H^2 - \mu \approx 0$$

The only positive root of this polynom is the solution

Planets	$\beta = 0$	$\beta = 0.5$	$\beta = 2$	$\beta = 4$	$\beta = 40$
Venus	167.0	39.29	19.76		4.42
Earth	234.9	57.13	28.75		6.44
Mars	319.7	53.88	27.00		6.04
HD 209458b	4.24			0.88	

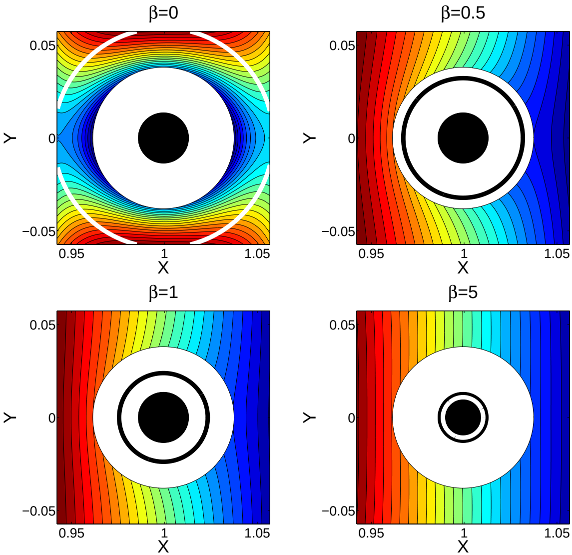
TABLE: Hill's sphere radius (or exopause) in planetary radii for Hydrogen with the effect of the radiation pressure ($\beta = 0, 0.5, 2, 40$) for different planets (Venus, Mars, Earth and HD 209458b).

Case study : HD 209458b



Topology of the equipotentials (red : high potential, blue : low potential) for increasing β values : 0, 0.5, 1 and 5. The decreasing circle corresponds to the circle passing through the Lagrange point L_2 : the Hill's sphere by definition. For high radiation pressures, the exopause goes below the exobase, limit of the dense atmosphere (white disk).

Case study : HD 209458b



For species with $\beta > 0.3$, the exopause is below the exobase

$\Longrightarrow$ the species is no longer gravitationally bounded to the planet, the species escapes from the atmosphere

$\Longrightarrow$ blow-off regime for Hydrogen ($\beta \approx 4$ according to Bourrier et al. (2013)) due to the radiation pressure and not to the Roche lobe location

Conclusions

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- Motion completely solved analytically for a particle subject to gravity and radiation pressure (arxiv.org/abs/1502.06701, under review)
- Accepted paper about this first part (density) : 10.1016/j.icarus.2015.08.023
- Future papers about the thermal escape flux (in prep.) and equipotentials (under review)