Radiation pressure effects on planetary exospheres and atmospheric erosion

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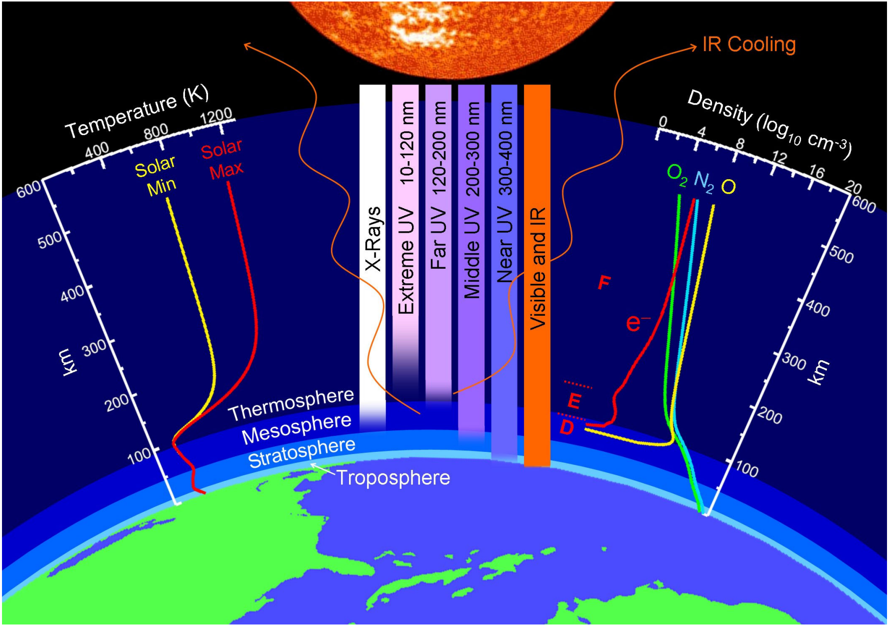
1. Introduction
2. Gravity vs radiation pressure
3. Influence of the radiation pressure on the number density
4. Influence of the radiation pressure on the escaping flux
5. Conclusions

Structure of the terrestrial atmospheres



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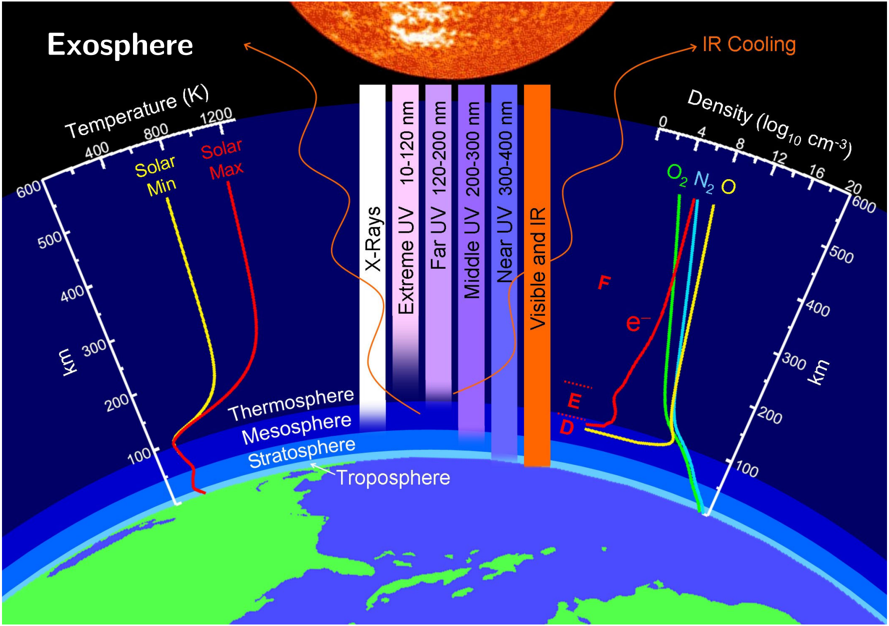

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  $\longrightarrow$ Fluid model non applicable for neutrals, need kinetic modelling.

How to model the neutral exosphere and the geocorona?

Probably, the simplest and most efficient way is using the Chamberlain (1963) model. Chamberlain (1963) proposed an analytical formula to estimate the exospheric density and the contribution of different exospheric population:

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

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

The ballistic particles are the main contribution near the planet.

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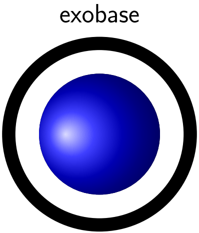

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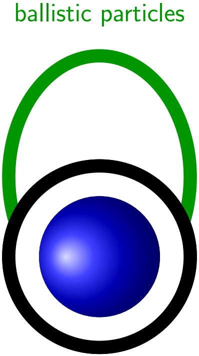

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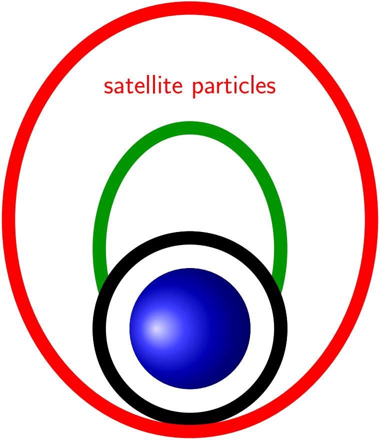

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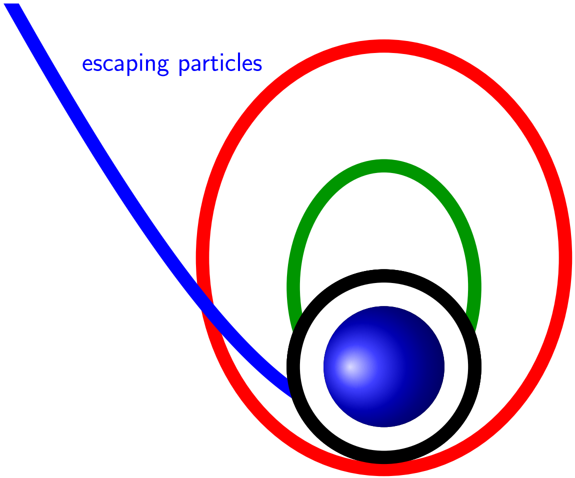


Chamberlain model

- Ballistic particles are the largest contributor for the number density near the planet
- Satellite particles are not consistent
- Escaping particles are at the origin of the erosion

This model suffers from 2 main assumptions:

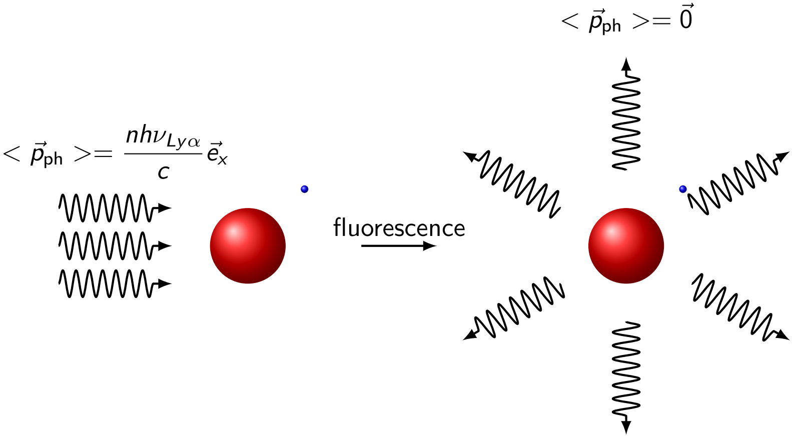
- only gravity
- no collisions

Are both or one of these assumptions wrong?

It exists other forces than gravity which can affect the dynamic of exospheric particles:

- gravity from the host star (e.g. for Hot Jupiters)
- centrifugal force (e.g. for Hot Jupiters)
- radiation pressure

Radiation pressure effect



Radiation pressure is efficient for species which absorb strong emission lines from the star: Hydrogen and Helium

At Earth, the radiation pressure on Hydrogen is 3 orders of magnitude ($\sim$ 0.0075 m.s^{-2}) less than gravity at the surface. So who cares?

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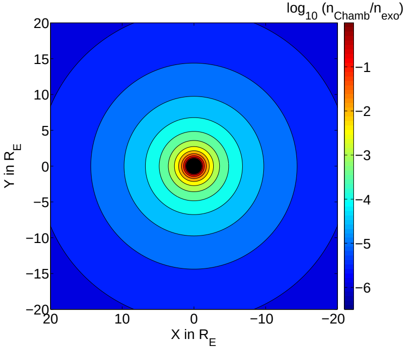
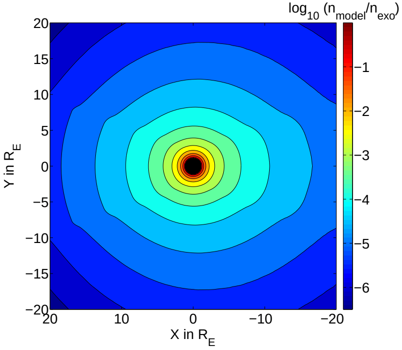
I do

For the maths, refer to Beth et al., Icarus, 2016a,b (based on Hamiltonian approach, developed originally by Bishop and Chamberlain, Icarus, 1989)

For the nice plots and schematics, next slides.

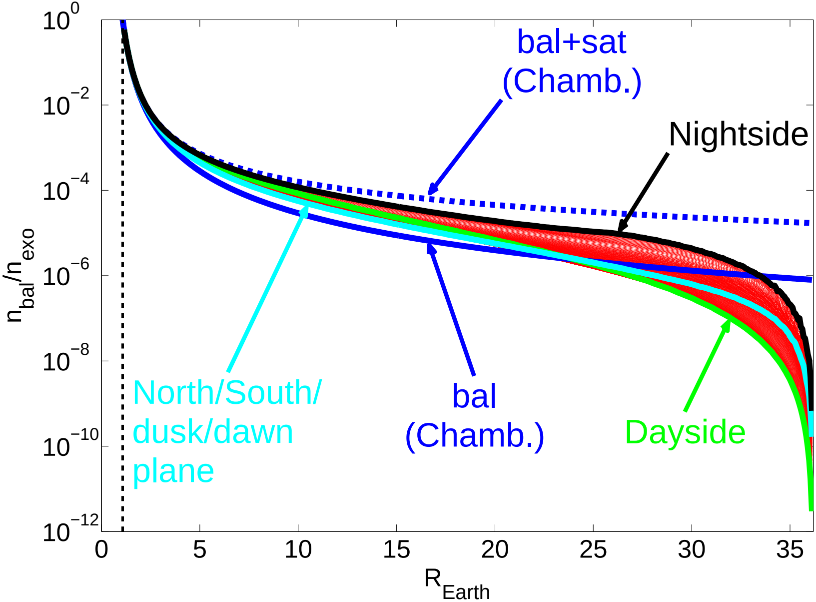
2D Number density with respect to the one at the exobase

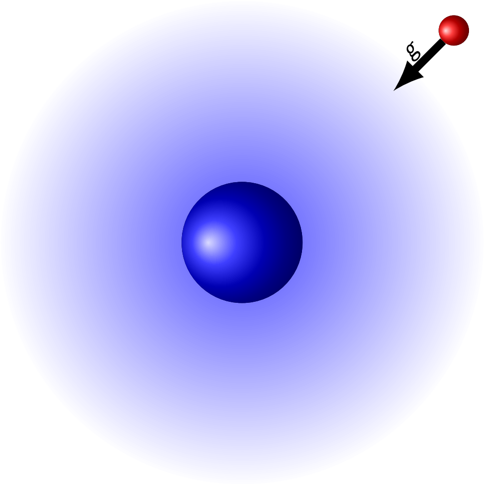


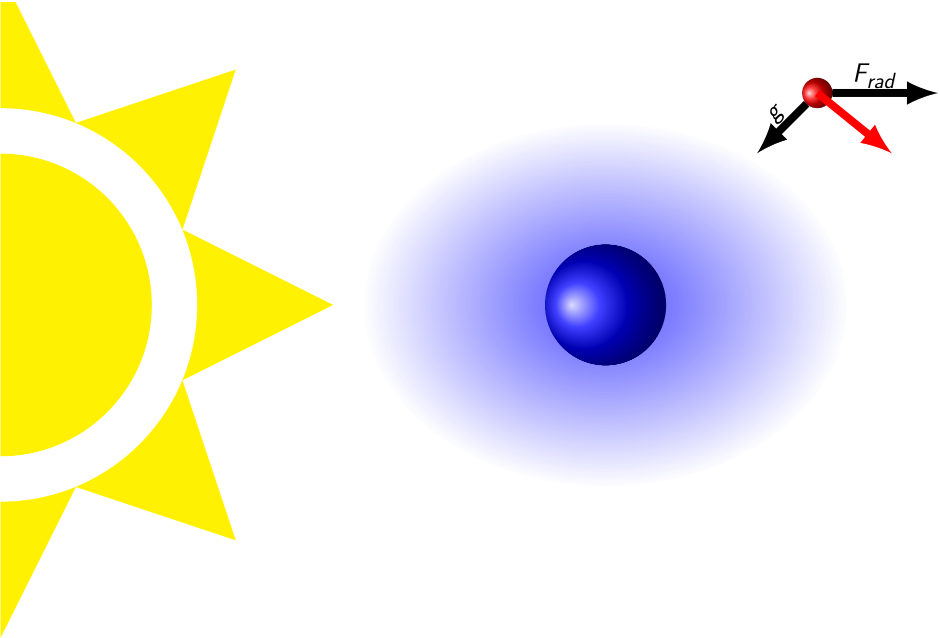


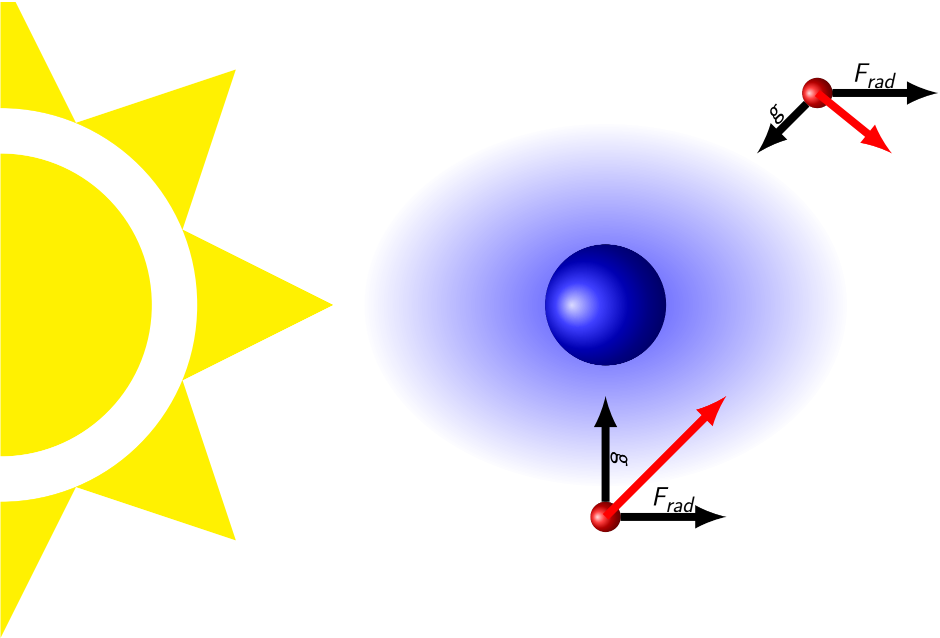
Beth et al. 2016b, Icarus

Radial number density profile

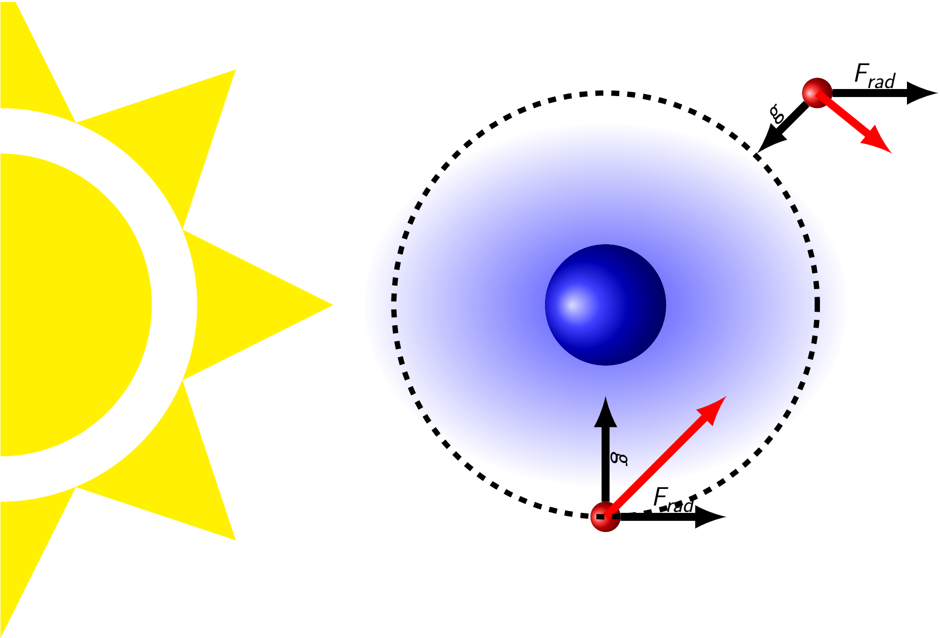


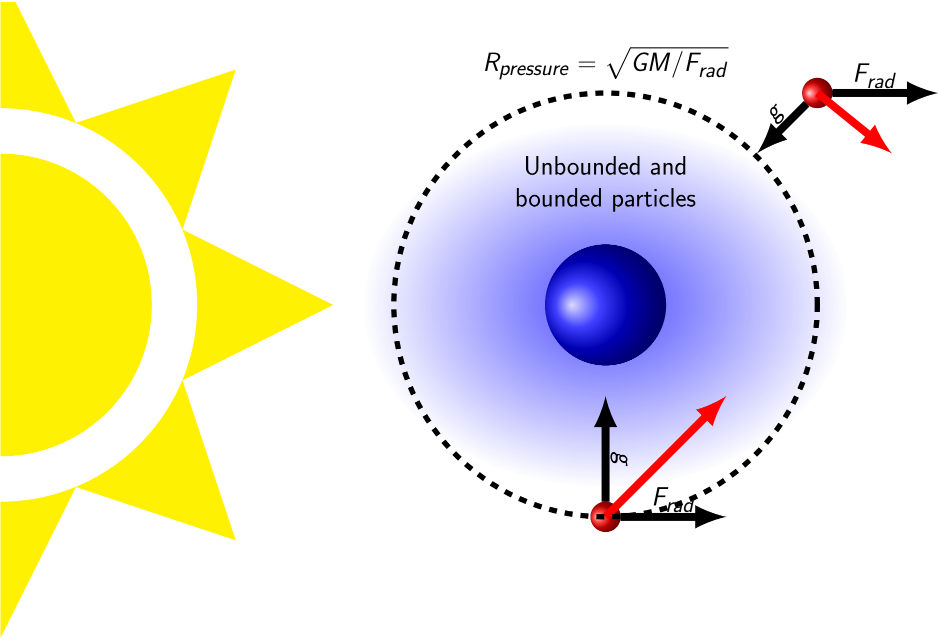

g


F_{rad}
g

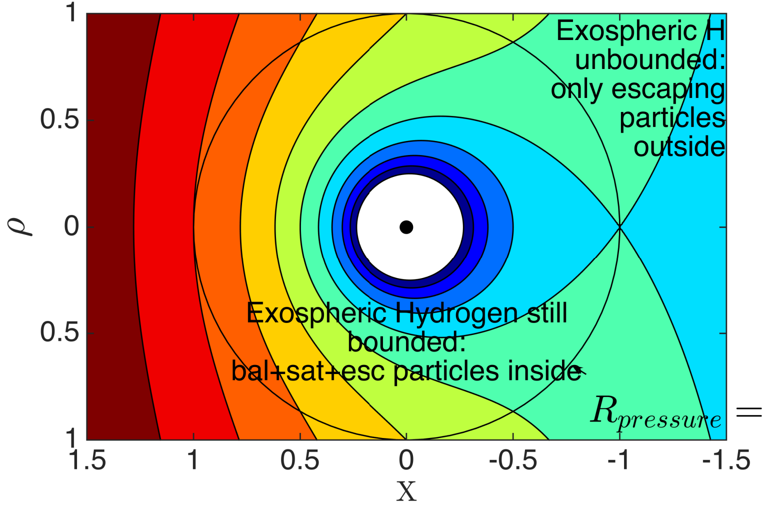


F_{rad}
g
g
F_{rad}


F_{rad}
g
g
F_{rad}


$R_{pressure} = \sqrt{GM/F_{rad}}$
F_{rad}
g
Unbounded and
bounded particles
g
F_{rad}

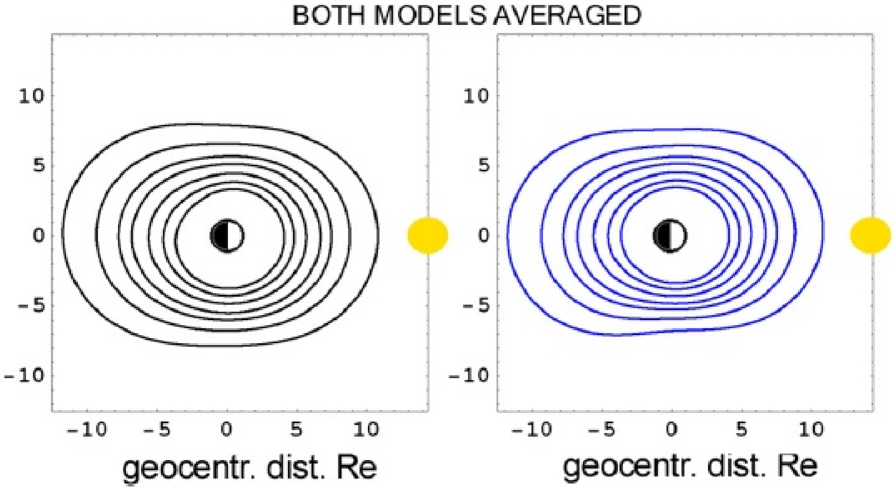
Equipotential



$$R_{pressure} = \sqrt{\frac{GM}{a}}$$

Comparison with observations

From Zoennchen et al, 2013



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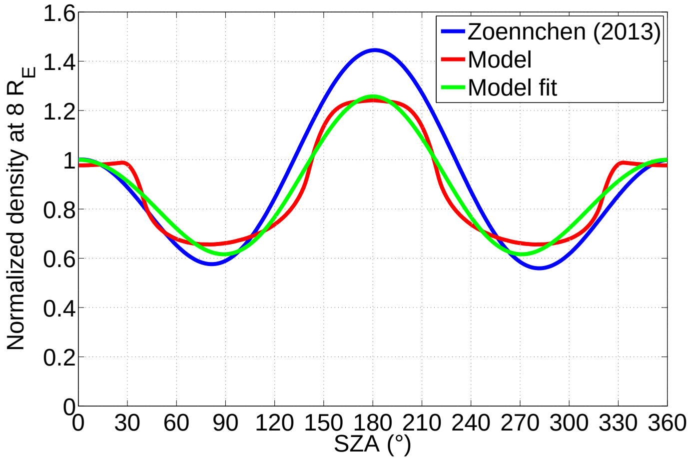

Qualitatively and quantitatively, the model reproduces quite well the variation in the equatorial plane.

Conclusions on the number density

Take-home messages

- Radiation pressure has a significant effect on the Earth corona
- Radiation pressure drives asymmetries of the Hydrogen geocorona
- The exosphere has another bound.

Effect on the escaping flux

At the location of the sub-solar point, it is possible to derive some kind of Jeans' formula for the escaping flux, taking into account the radiation pressure, which is the flux of unbounded particles.

Jeans' formula

$$\mathcal{F}_{Jeans} = \frac{n_{exo}}{2\sqrt{\pi}}\sqrt{\frac{2k_B T_{exo}}{m}}(1+\lambda_c)\exp(-\lambda_c)$$

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It has not been published yet

A new parameter

To assess the effect of the effect of the radiation pressure, we introduce a new parameter:

$$\lambda_a = \frac{\sqrt{GMa}m}{k_B T_{exo}}$$

$$\lambda_c = \frac{GMm}{k_B T_{exo} r_{exo}}$$

$$\frac{\lambda_a}{\lambda_c} = \frac{r_{exo}}{R_{pressure}}$$

An updated Jeans' formula

I skip the mathematical details...

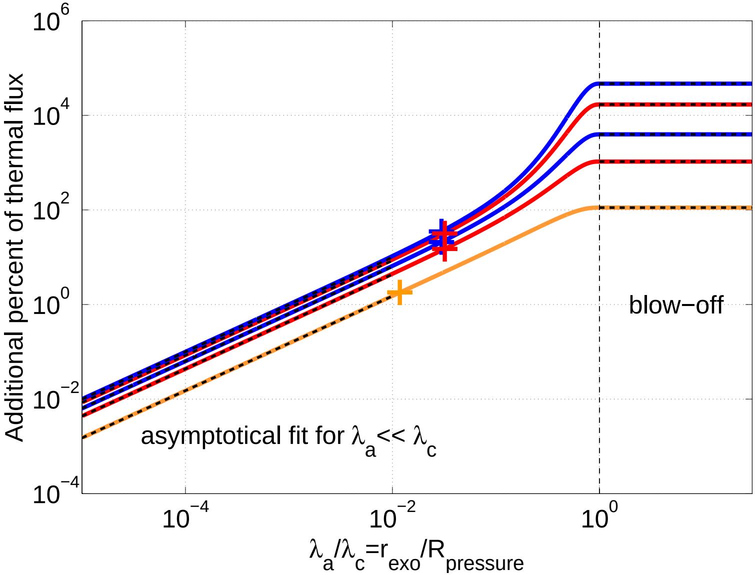
An updated Jeans' formula

I skip the mathematical details... Ok for just one formula

New escaping formula

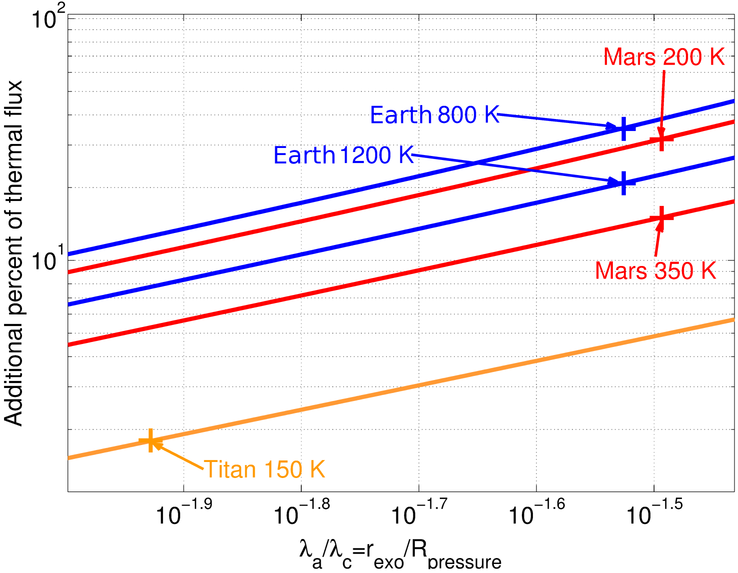
$$\mathcal{F} = \frac{n_{exo}}{2\sqrt{\pi}}\sqrt{\frac{2k_B T}{m}} \exp\left(-\frac{(\lambda_c - \lambda_a)^2}{\lambda_c}\right) \times \left\{1 - \frac{\exp[-\lambda_a(1 - \lambda_a/\lambda_c)]}{\lambda_a} \sinh[\lambda_a(1 - \lambda_a/\lambda_c)]\right\}$$

Error on the escaping flux

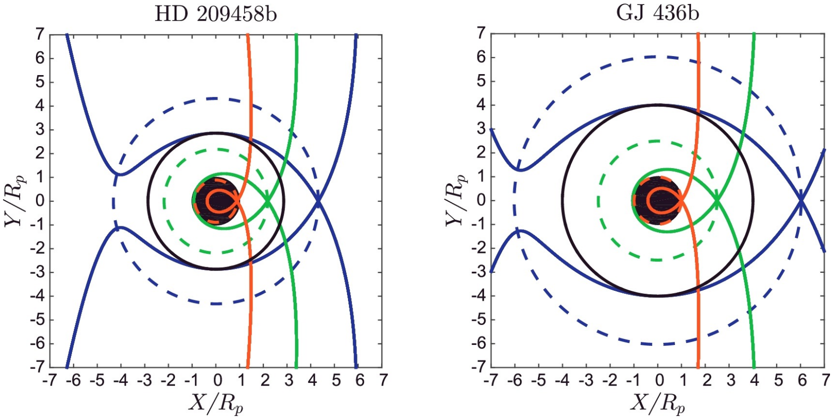


- Increasing the radiation pressure, even at the sub-solar point, increases the escaping flux
- The increase is more significant for large λ_c: effect of the radiation pressure is worse on cold, expanded exospheres and around heavy bodies.

Error on the escaping flux



Application to hot Jupiters



- Depending on the solar conditions, the escaping flux is underestimated by 20-30% with Jeans' formula nowadays at Earth
- The escaping flux is maximum for $r_{exo} > R_{pressure}$,
  $\mathcal{F} = \frac{n_{exo}}{2\sqrt{\pi}}\sqrt{\frac{2k_B T}{m}}$

Conclusions on the escaping flux

Take-home messages

- Radiation pressure increases the escaping flux at the sub-solar point
- It virtually decreases λ_c (introducing λ_a is equivalent to lessen λ_c in the Jeans' formula)
- For strong radiation pressure ($r_{exo} \geq R_{pressure}$), the atmosphere started to be in blow-off
- (bonus) It can explain the escaping flux of Hot Jupiters (Beth et al. 2016c)

Conclusions

- The radiation pressure shapes the Earth hydrogen geocorona and those of terrestrial planets
- It induces the asymmetries observed in remote sensing at Earth
- It slightly increases the escaping flux.

Perspectives

- Need in-situ measurements
- The radiation pressure is efficient on Helium and should be investigated as well
- Determining the distribution of escaping particles
- Assess the escaping flux at different solar zenith angle