EPSC Abstracts
Vol. 10, EPSC2015-572, 2015
European Planetary Science Congress 2015

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

A. Beth (1), P. Garnier (2,3), D. Toublanc (2,3), I. Dandouras (2,3), C. Mazelle (2,3)
(1) Dpt of Physics, Imperial College London, London, United Kingdom (a.beth@imperial.ac.uk)
(2) Université de Toulouse; UPS-OMP; IRAP; Toulouse, France
(3) CNRS; IRAP; 9 Av. colonel Roche, BP 44346, F-31028 Toulouse cedex 4, France

Abstract

The uppermost layer of the atmosphere, the exosphere, is not well-known in its global structure since the densities are very low compared to instrument detection capabilities. Because of rare collisions and high Knudsen numbers, the motion of light species (H, H_2, ...) in the corona is essentially determined by the external forces : the gravitation from the planet, the radiation pressure, as well the stellar gravity.
In this work, we calculate rigorously and analytically, based on the Hamiltonian mechanics and Liouville theorem, the impact of the radiation pressure and gravitation from the planet on the structure of the exosphere. This approach was partially used by Bishop and Chamberlain (1989) but only in the 2D case : we extend it to the 3D case. Assuming a collisionless exosphere and a constant radiation pressure near the planet, we determine the density profiles for ballistic particles (the main contribution for densities in the lower exosphere) for light species as a function of the angle with respect to the Sun direction. We also obtain an analytical formula for the escape flux at the subsolar point, which can be compared with the Jeans' escape flux.
Finally, we study the effect of the radiation pressure on the zero velocity curves, position of the Roche lobe and Hill's region for the well-known Three-Body problem especially for Hot Jupiters and discuss about the validity of our model. The goal is to bring some constraints on modelling of exoplanet atmospheres.

1. Introduction

The exosphere is the upper layer of the atmosphere where the densities are low compared to intrument detection capabilities. Thus, we need to model this part of the atmosphere to explain observations of densities or escape flux from exoplanet atmospheres.
In this region, the gas is directly in interaction with the interplanetary medium: the gas is subject to both planet and stellar gravities, scarse collisions and radiation pressure. We propose a way to model the escape flux, as well as the densities of one type of particles in a collisionless exosphere: the ballistic particles. These are linked to the planet by gravitation and not enough pushed away by the radiation pressure to escape.

2. Model and results

For this problem, we use a hamiltonian approach. In the presence of the radiation pressure and the gravitational force, the Hamiltonian is given by:

$$\mathcal{H} = \frac{p_r^2}{2m} + \frac{p_\theta^2}{2mr^2} + \frac{p_\phi^2}{2mr^2 \sin^2\theta} - \frac{GMm}{r} + ma\cos\theta$$

where r is the distance from the planet, θ the angle between the particle and the Sun, ϕ the angle between the particle and the ecliptic plane, p_r, p_θ and p_ϕ are the conjugate momenta, a the constant acceleration due to the radiation pressure. It is then necessary to use a parabolic system of coordinates:

$$u = r(1+\cos\theta) \;\; w = r(1-\cos\theta)$$

and the Hamiltonian becomes:

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

We define the Jeans parameter $\lambda(r) = GMm/k_B T_{exo} r$, $R_{pressure} = \sqrt{GM/a}$, $\lambda_c = \lambda(r_{exo})$ where r_{exo} is the distance of the exobase from the center of the planet and $\lambda_a = \lambda(R_{pressure})$.

Also, we estimate analytically the escape flux at the subsolar point including the effect of radiation pressure:

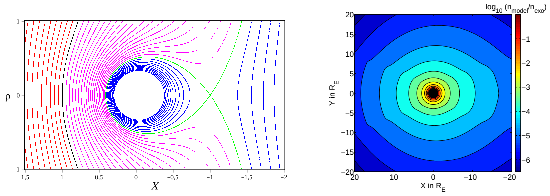

Figure 1: Zero velocity curves (dimension less distance) for our problem and ballistic particles density at Earth for hydrogen and $T_{exo} = 800\ K$

$$\mathcal{F} = \frac{n_{exo} U_{th}}{2\sqrt{\pi}} \frac{\lambda_c}{\lambda_a} \exp\left(-\frac{(\lambda_c - \lambda_a)^2}{\lambda_c}\right) \times$$

$$\left(1 - \frac{\exp[-\lambda_a(1 - \lambda_a/\lambda_c)]}{\lambda_a} \sinh[\lambda_a(1 - \lambda_a/\lambda_c)]\right)$$

for $r_{exo} < R_{pressure}$, $\mathcal{F} = n_{exo} U_{th}/2\sqrt{\pi}$, for $r_{exo} > R_{pressure}$ (blow-off regime); with $U_{th} = \sqrt{2 k_B T_{exo}/m}$

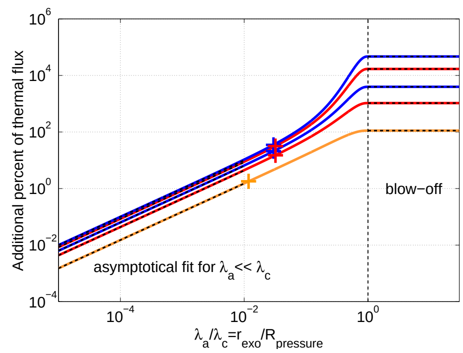

Figure 2: Relative difference between our model escape flux and the Jeans' escape flux at the subsolar point as a function of the radiation pressure at Earth (blue), Mars (red) and Titan (orange). The crosses indicate the real values at Earth (blue), Mars (red) and Titan (orange).

Finally, we study the effect of the radiation pressure on the Roche lobe position. We derive an analytical formula to determine approximatively (with a maximum error of $\sim 3\%$):

$$R_H = \frac{\beta}{9}\left(2\ \cosh\left(\frac{1}{3}\ \text{argcosh}\left(\frac{243\mu}{2\beta^3} - 1\right)\right) - 1\right)$$

for $\beta < 3\sqrt[3]{9\mu/4}$ and

$$R_H = \frac{\beta}{9}\left(2\ \cos\left(\frac{1}{3}\ \arccos\left(\frac{243\mu}{2\beta^3} - 1\right)\right) - 1\right)$$

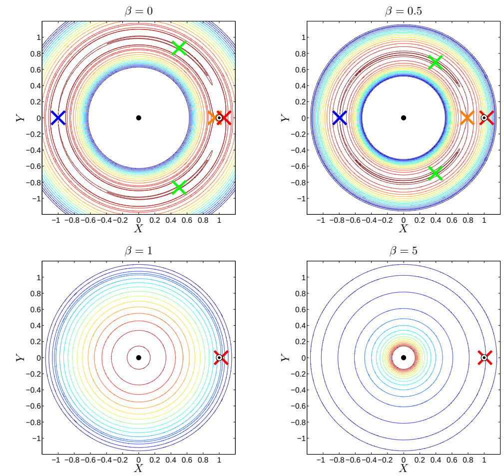

Figure 3: Levels of effective potential for Ω for $\beta = 0$ (pure CR3BP, upper panels), $0.5, 1, 5$ for HD 209458b. The crosses define the Lagrange points: L_1 (orange), L_2 (red), L_3 (blue), L_4 and L_5 (green). The central point corresponds to the star position. The black point around $(1, 0)$ corresponds to the true planetary size and the surrounding white disk to the atmosphere with its supposed size.

for $\beta > 3\sqrt[3]{9\mu/4}$.

This modification could impact a lot the evolution, the escape, the stability of the surrounding atmosphere especially for Hot Jupiters. However, it could also affect strongly the primitive planetary atmospheres of the early Solar System.

3. Summary and Conclusions

We propose a semi-analytical model to estimate ballistic particles densities in planetary exospheres (in the Solar System or beyond) using Hamiltonian mechanics. We assume a collisionless exosphere. The results are in good agreement with Earth observations of day/night/dusk/dawn asymmetries. Moreover, we derive an analytical formula for the escape flux including the radiation pressure and show, for the Earth case in particular an enhancement of the escape flux by up to 30% compared with Jeans' escape formula. Finally, the radiation pressure can induce a large effect on the Three-Body, especially for planets close to their host star like HD 209458b and generally Hot Jupiters. We derive a new formula in order to determine the true size of the Hill's sphere subject to the radiation pressure.