Evaporation rate of hot Jupiters and formation of Chthonian planets

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Abstract. Among the hundred of known extrasolar planets, about 15% are closer than 0.1 AU from their parent stars. But there are extremely few detections of planets orbiting in less than 3 days. At this limit the planet HD 209458b has been found to have an extended upper atmosphere of escaping hydrogen. This suggests that the so-called hot Jupiters which are close to their parent stars could evaporate.

Here we estimate the evaporation rate of hydrogen from extrasolar planets in the star vicinity. With high exospheric temperatures, and owing to the tidal forces, planets evaporate through a geometrical blow-off. This may explain the absence of Jupiter mass planets below a critical distance from the stars. Below this critical distance, we infer the existence of a new class of planets made of the residual central core of former hot Jupiters, which we propose to call the “Chthonian” planets.

Following the recent discovery of a significant escape of atomic hydrogen from the planet orbiting HD 209458 (Vidal-Madjar et al. 2003), we propose to evaluate the escape flux from the upper atmosphere of hot Jupiters under the influence of the strong tidal forces from their parent stars. This escape flux had previously been estimated (Guillot et al. 1996), but the conclusion that the mass loss is not significant was based on two hypotheses which need to be revisited.

First, the black body radiative equilibrium used to calculate the temperature of the upper atmosphere (Schneider et al. 1998) is inappropriate because it does not apply to the low density upper atmosphere. Observations in the Solar System show that the temperature of a planetary upper atmosphere (thermosphere, exosphere) is much higher than the effective temperature of the bottom atmosphere. For example, whereas the temperatures in the Earth and Jupiter are around 200 K and 120 K respectively at the level of the tropopause, they reach 1000 K in the thermosphere of these two planets. Although these observed high temperatures in the planets of our own Solar System remain unexplained, there are some clues that a combination of the extreme and far ultraviolet fluxes with the Solar wind is responsible for the heating.

The second important hypothesis is tidal force, which modifies the gravity of hot Jupiters. The common hypothesis is to neglect that effect as for isolated planets far from their star. However, tidal forces have a significant influence on the density distribution in the upper atmosphere of hot Jupiters.
At a given temperature the escape flux can be calculated using the Jeans’ escape estimate. *Jeans’ escape* refers to the escape of atoms and molecules whose velocities are in the tail of the Boltzmann distribution and which have enough energy to escape the planet gravity. The flux is calculated at the top of the thermosphere, that is the level above which the atoms and molecules have no collisions. The exobase is usually defined as the location above which the mean free path is larger than the scale height of the atmosphere. Here we extend this idea by defining the exobase as the location above which the mean free path is larger than the distance to the Roche lobe of the planet. Thus, the exobase is the location above which the atoms and molecules can definitively escape the planet.

We computed the escape flux of atomic and molecular hydrogen as a function of the upper atmosphere temperature. From this, we can derive the corresponding life time needed to evaporate the total mass of the planet. For $T \gtrsim 7000$ K, the $\text{H} \text{I}$ escape flux is larger than the minimum flux of $10^{10} \text{g s}^{-1}$ determined from Ly-$\alpha$ observations (Vidal-Madjar et al. 2003).

Although the mechanism responsible for the heating of the upper atmosphere of the planets in the Solar System is not fully identified, we can hint a simple estimate of a plausible temperature from the comparison of the heating and cooling mechanisms. A lower limit of the heating can be estimated from the energy flux of the stellar extreme ultraviolet and the Ly-$\alpha$ photons. The cooling is due to a combination of the heat conduction toward the cooler bottom atmosphere, the collisional ionization and excitation of the $\text{H} \text{I}$ electronic levels, and the evaporation at the top of the upper atmosphere. Thus, a lower limit to the temperature can be estimated by the energy balance. With the parameters of HD 209458b, we evaluate the temperature in the upper atmosphere to be at least $\sim 10000$ K. With this temperature the present evaporation rate of hydrogen from HD 209458b must be $\sim 1$ to $5 \times 10^{11} \text{g s}^{-1}$. This is in agreement with the lower limit found from the HST Ly-$\alpha$ observations. Assuming an age of $5 \times 10^9$ years, HD 209458b may have lost about 1% to 7% of its mass.

Finally, we also estimated the life time of a given planet as a function of its mass and orbital distance. We found that planets with orbital periods shorter than 2 to 3 days have very short life time. This may explain that only few planets have been detected with periods shorter than 3 days. Moreover, low-mass planets have also short life time. This means that the nature of these low-mass hot Jupiters should evolve with time. These planets should lose a large fraction of their hydrogen. This process may lead to planets with an hydrogen-poor atmosphere, or even with no more atmosphere at all. The emergence of the inside core of former and evaporated hot Jupiter may give rise to a new class of planets which we proposed to call “Chthonian” planets in reference to the Greek god Khthon ("Chthonian" is used to name the Greek deities who come from hot infernal underground).

References:
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