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Letter to the Editor

Atmospheric escape from hot Jupiters

A. Lecavelier des Etangs[1], A. Vidal-Madjar[1], J. C. McConnell[2], and G. Hébrard[1]

[1] Institut d'Astrophysique de Paris, CNRS, 98bis boulevard Arago, 75014 Paris, France
[2] Department of Earth and Atmospheric Science, York University, North York, Ontario, Canada

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Abstract. The extra-solar planet HD 209458b has been found to have an extended atmosphere of escaping atomic hydrogen (Vidal-Madjar et al. 2003), suggesting that "hot Jupiters" closer to their parent stars could evaporate. Here we estimate the atmospheric escape (so called evaporation rate) from hot Jupiters and their corresponding life time against evaporation. The calculated evaporation rate of HD 209458b is in excellent agreement with the H I Lyman-α observations. We find that the tidal forces and high temperatures in the upper atmosphere must be taken into account to obtain reliable estimate of the atmospheric escape. Because of the tidal forces, we show that there is a new escape mechanism at intermediate temperatures at which the exobase reaches the Roche lobe. From an energy balance, we can estimate plausible values for the planetary exospheric temperatures, and thus obtain typical life times of planets as a function of their mass and orbital distance.

Key words. star: individual: HD 209458 – stars: planetary systems

1. Introduction

Among the more than one hundred extra-solar planets known, over 15% are closer than 0.1 AU from the central star. Except for a possible transiting planet (OGLE-TR-56b, Konacki et al. 2003; Torres et al. 2003), there are no detection of planets closer than about 0.04 AU. Following the discovery that the planet HD 209458b shows a surprisingly large escape of atomic hydrogen (Vidal-Madjar et al. 2003; confirmed by Vidal-Madjar et al. 2004), the escape flux from hot Jupiters needs to be evaluated. Already in 1995, together with the release of the first hot Jupiter discovery (Mayor & Queloz 1995), Burrows & Lunine (1995) highlighted the evaporation issue. But Guillot et al. (1996) concluded that the mass loss was not significant. However their estimates did not consider two factors which need to be addressed: the influence of the strong tidal forces from the neighboring parent stars, and the high upper atmosphere temperature (Hébrard et al. 2003).

2. The upper atmosphere model

Radiative equilibrium is commonly used to calculate the temperature of the upper atmosphere (see Schneider et al. 1998). But this is not appropriate because it does not apply to the low density upper atmosphere. As an example, in the Solar system, the temperature of planetary upper atmospheres (thermosphere, exosphere) is much higher than $T_{\rm eff}$, the effective temperature of the lower atmosphere. For Earth and Jupiter, $T_{\rm eff}$ are ~250 K and 150 K, while thermospheric temperatures are ~1000 K for both planets (Chamberlain & Hunten 1987). Although the observed high temperatures in the giant planets are not yet explained, extreme and far ultraviolet fluxes, Solar wind and perhaps gravity waves may contribute to the heating in uncertain amounts (e.g., Hunten & Dessler 1977).

The atmospheric escape flux strongly depends on the temperature profile of the atmosphere. As the temperature of the upper atmosphere of extra-solar planets is not known, in a first step, we will use it as an input parameter: $T_{\rm up}$. We consider a simple atmospheric structure similar to that observed in the giant planets of the Solar system, that is a two level temperature structure: $T_{\rm eff}$ in the lower atmosphere and $T_{\rm up}$ above. We assume that the lower atmosphere (up to the thermobase) is mainly composed of molecular hydrogen at $T_{\rm eff}$. Above that level, in the thermosphere and exosphere, the gas is a mixture of atomic and molecular hydrogen at $T_{\rm up}$ (Fig. 1).

The quantitative results presented in this letter do not depend on the estimated $T_{\rm eff}$, but on the density at the thermobase, $n_{\rm H\,I}$ and $n_{\rm H_2}$ for atomic and molecular hydrogen, respectively. In the following we will use three different estimates of these densities. In the case of Jupiter and Saturn, H_2 is the main constituent at the thermobase, where the temperature transition is observed to occur for $n_{\rm H\,I} \simeq 2\times10^9$ cm^{-3} and $n_{\rm H_2} \simeq 1\times10^{11}$ cm^{-3} (Chamberlain & Hunten 1987); these values will be used for the Model A. By evaluating the production of atomic hydrogen with realistic condition for the lower atmosphere of HD 209458b, Liang et al. (2003) have shown that the H I mixing ratio could be about 10% at the thermobase. We thus use the corresponding $n_{\rm H\,I} = 1\times10^{10}$ cm^{-3} and $n_{\rm H_2} = 9\times10^{10}$ cm^{-3} for the intermediate Model B. Finally, at high thermospheric temperatures, it is likely that most of

Send offprint requests to: A. Lecavelier des Etangs,
e-mail: lecaveli@iap.fr

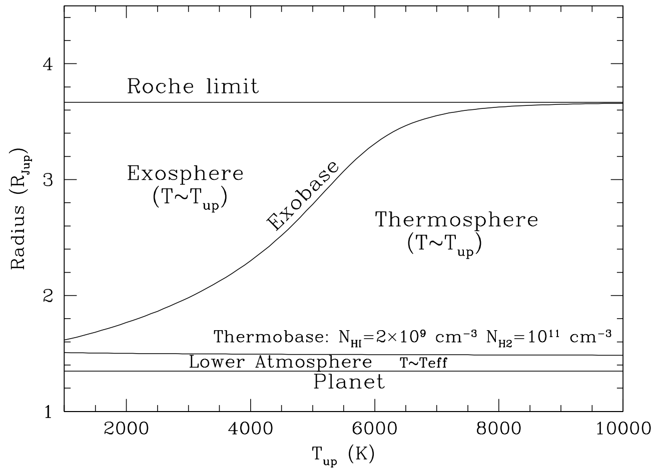

Fig. 1. Vertical structure of the atmosphere of HD 259458b as a function of the temperature of the upper atmosphere (Model A). At the top of the thermosphere, the exobase is the critical level where the mean free path is equal to the distance to the Roche lobe. For high temperatures, the exobase reaches the Roche lobe; this leads to a *geometrical blow-off*.

the molecular hydrogen is dissociated into atomic hydrogen (Coustenis et al. 1998); we use $n_{\rm H\,I} = 2\times10^{11}$ cm^{-3} and $n_{\rm H_2} = 0$ cm^{-3} for the corresponding Model C.

3. The atmospheric escape

The atmospheric escape critically depends on atmospheric temperatures. Below a critical temperature, $T_{\rm c}$, the escape flux can be calculated using the Jeans escape estimate which refers to the escape of particles whose velocity is in the tail of the Boltzmann distribution and that have enough energy to escape the planets gravity. For temperatures above $T_{\rm c}$, the kinetic energy of the atoms or molecules is sufficient to overcome gravitational forces and they can stream, or blow-off. For Jeans escape the flux is calculated at a critical level corresponding to the exobase (Hunten et al. 1989). This critical level is the level above which particles can freely escape without collisions. The exobase is usually defined by the place above which the mean free path ($1/nQ$) is larger than H, the scale height of the atmosphere, where n is the volume density. This definition results from the approximate calculation of the integrated collisional cross-section (Q) from the exobase to infinity: $\int_{\rm exobase}^{\infty} n(r)Q{\rm d}r \approx n_{\rm exo}HQ = 1$, where $n_{\rm exo}$ is the density at the exobase. Here this idea must be generalized to take into account the particular geometry of hot Jupiters; we define the exobase by the place above which the mean free path is larger than the distance to the Roche lobe of the planet: $\int_{\rm exobase}^{\rm Roche\ lobe} n(r)Q{\rm d}r = 1$. The Roche lobe is the last equipotential around the planet beyond which the equipotentials are open to infinity or to encompass the star. Thus the exobase is the level above which atoms and molecules can definitively escape the planet. Note that in the case of an isolated planet, because the Roche lobe is at infinite distance, the two definitions are identical. Then, the total escape flux from the planet is given by $\dot{M} = 4\pi r_{\rm exo}^2 \times n_{\rm exo}\mu v_T/(2\sqrt{\pi}) \times {\rm e}^{-\lambda}(\lambda+1)$, where μ is the mass of the escaping elements (H I and H_2), $r_{\rm exo}$ is the radius of the exobase, and v_T is the thermal velocity at temperature T (Chamberlain & Hunten 1987). λ is defined by $\lambda = -\chi\mu/kT$, where χ is the gravitational potential. We calculated the density profile in the atmosphere using the barometric law: $\boldsymbol{\nabla} n = n\boldsymbol{\nabla}\lambda$. Recapture of escaped particles is not possible because of the high radiation pressure pushing away hydrogen atoms at hundred of kilometer per seconds (Vidal-Madjar et al. 2003).

We can see from Fig. 1 that between the classical Jeans escape at low temperatures and the dynamical blow-off of the atmosphere at high temperatures, the tidal forces lead to a new escape mechanism at intermediate temperatures. Indeed, for HD 209458b (d = 0.047 AU, $M_{\rm p} = 0.69\,M_{\rm Jup}$, and $R_{\rm p} = 1.35\,R_{\rm Jup}$) and $T_{\rm up}$ above ~5000 K, the exobase comes close to the Roche lobe, and the kinetic energy is similar to the potential energy needed to reach this limit. In that case, the escape mechanism is a *geometrical blow-off* which is due to the filling up of the Roche lobe by the thermosphere pulled up by the tidal forces. Indeed, the dynamical blow-off is obtained when the escape velocity $v_{\rm esc}$ is of the order of (or smaller than) the thermal velocity v_T, that is for small value of $\lambda_{\rm exo}$ ($\lambda = v_{\rm esc}^2/v_T^2$). With the characteristics of HD 209458b, the dynamical blow-off takes place for temperatures above 20 000 K. However, at temperatures between 5000 K and 20 000 K, although $\lambda_{\rm exo} \gg 1$, we have $\lambda_{\rm exo} - \lambda_{\rm Roche} \leq 1$, and most of the gas at the exobase can freely reach the Roche lobe. This geometrical blow-off is due to the spatial proximity of the Roche lobe through which the gas can escape the planet.

4. Tidal forces

In the case of hot Jupiters, the planet's gravity is substantially modified by stellar tidal forces. The common assumption has been to neglect tidal forces by considering isolated planets far from their star. But tidal forces have a significant influence on the density distribution in the upper atmosphere of hot Jupiters. In order to calculate the potential energy χ, we include the difference between the stellar gravitation and the centrifugal effect in the orbiting planet reference frame, which results in the tidal forces. The equipotentials are modified, from quasi-spherical in the lower atmosphere to asymmetric elongated shapes at the level of the Roche lobe. As a result, χ, hence the vertical density distribution, strongly depend on the location in both longitude and latitude on the planet (θ, ϕ). We calculate the escape rate as the sum of $\dot{M}(\theta,\phi)$, the escape flux as a function of longitude and latitude. Even with a uniform temperature, the escape flux per unit area is larger toward the star and in the opposite direction (Fig. 2).

Finally, using the above, we estimate the total escape flux of atomic and molecular hydrogen as a function of the upper atmosphere temperature for HD 209458b (Fig. 3). For temperature above 8000 K (Model A), 7000 K (Model B) and 6000 K (Model C), the H I escape flux is larger than the minimum flux of 10^{10} g s^{-1} needed to explain the occultation depth of 15% as observed in Lyman α (Vidal-Madjar et al. 2003). From the escape rate, we can derive the corresponding life time needed to evaporate the total mass of the planet $t_1 = M_{\rm p}/\dot{M}$. However when the planet mass decreases, the evaporation rate increases.

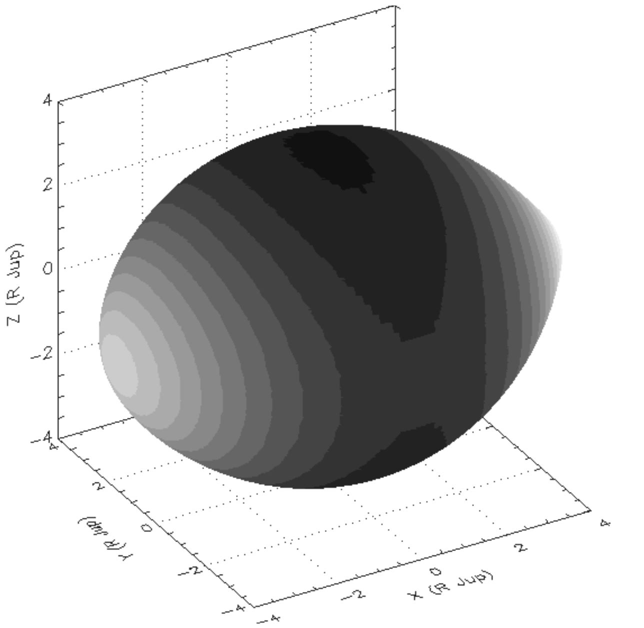

Fig. 2. Shape of the exobase and the corresponding escape rate (Model A, $T_{\rm up} = 11\,100$ K). Light grey is for the large escape rates (10^{10} g s^{-1} str^{-1}) and black is for the small escape rates ($<5 \times 10^{9}$ g s^{-1} str^{-1}). The star is on the X-axis toward positive coordinates. The escape rate is the largest toward the star and in the opposite direction.

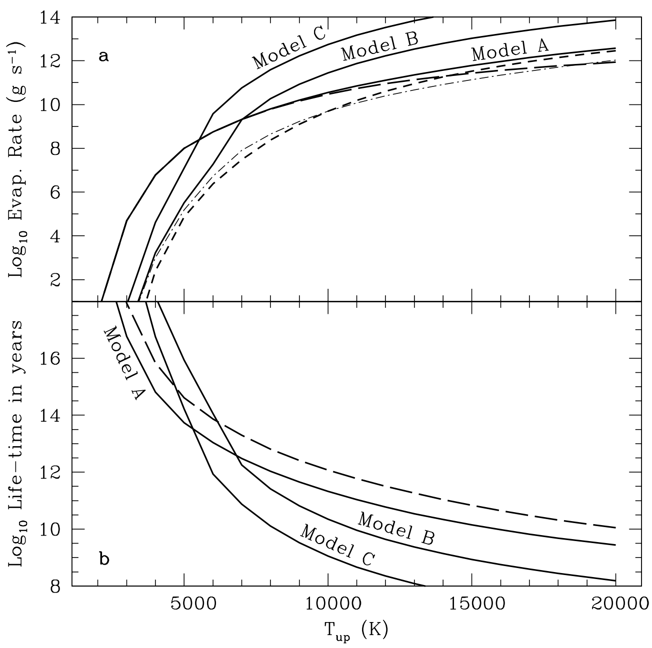

Fig. 3. Escape flux and life time of HD 209458b as a function of $T_{\rm up}$. The results from various models show the uncertainty due to the lack of constraint on the densities at the thermobase. **a)** shows the escape flux of H I (long dashed) and H_2 (short dashed) in the Model A, and the total escape flux (solid lines) for models A, B and C. For the Model A, the total escape flux from an isolated planet (without tidal forces) is plotted with the dot-dashed line. The tidal forces increase the evaporation rate by one to two orders of magnitude. **b)** shows the planet life time. A first estimate is obtained from the instantaneous escape flux for Model A (t_1, dashed line). Taking into account the planet's mass decrease with time, we find shorter life times (t_2, solid lines).

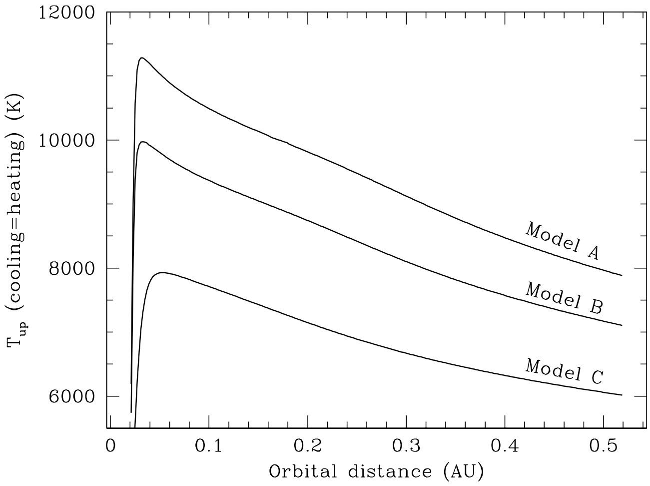

Fig. 4. Upper atmosphere temperature estimated from the energy balance as a function of the orbital distance of a 0.69 $M_{\rm Jup}$ planet. The input energy is $2.7 \times (d/1\ {\rm AU})^{-2}$ erg cm^{-2} s^{-1}. Below 0.04 AU, the temperature decreases because the large escape rate cools down the thermosphere.

This results in a shorter life time given by $t_2 = \int {\rm d}M/\dot{M}$, which is typically shorter than t_1 by a factor of 5 to 10 (Fig. 3b).

5. The temperature of the upper atmosphere

Although the mechanism responsible for the heating of the upper atmospheres in the Solar system is not fully identified, we obtain a plausible estimate of $T_{\rm up}$ from a comparison of heating and cooling mechanisms. A lower limit of the heating can be estimated from the energy flux of both the stellar extreme ultraviolet (EUV) and Lyman α photons. Using the EUV and a monte-carlo simulation of the multiple scattering of Lyman α photons in the thermosphere, we estimate the minimum energy input to be $G = 2.7 \times (d/1\,{\rm AU})^{-2}$ erg cm^{-2} s^{-1}, where d is the orbital distance to the star. The cooling is due to a combination of the heat conduction toward the cooler lower atmosphere, collisional exitation of the H I electronic levels, collisional ionization (photo-ionization is negligible), and cooling by escaping atoms and molecules carrying off their kinetic energy. We derive the ionization fraction and the collisonal cooling following Spitzer (1978) and Osterbrock (1989) for atomic and molecular hydrogen clouds. With the HD 209458b characteristics, the ionization fraction is barely above 0.01. We calculated the heat conduction following the derivation given by Hunten & Dessler (1977).

If we apply this calculation to Jupiter with UV heating only, we find a temperature rise at the thermobase as low as ~15 K (Strobel & Smith 1973); clearly other heating mechanisms are at work in Jupiter (Hunten & Dessler 1977). Considering the UV heating only, the energy balance provides a lower limit to the thermospheric temperature (Fig. 4). For HD 209458b, we evaluate the lower limit of $T_{\rm up}$ to be about 11 100 K, 9800 K and 7900 K for Models A, B and C, respectively. Cooling is dominated by atmospheric escape and collisonal excitation of H I. With these temperatures, the present evaporation rates of atomic and molecular hydrogen from HD 209458b are

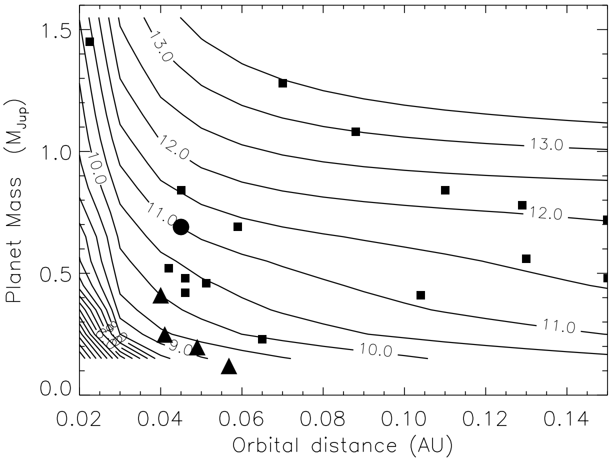

Fig. 5. Contour plot of the planet life time ($\log_{10} t_2$/year) as a function of the mass and orbital distance (Model A). The temperature is obtained from the energy balance and is varying with time. We obtain similar numerical estimates and contour plots for Model B and C. The squares show the positions of detected planets. OGLE-TR-56b is at the upper left conner. HD 209458b is shown by a circle. HD 49674b, HD 46375b, HD 76700b, and HD 83443b (triangles) have life time of about 10^9 years. These planets must have lost a large fraction of their hydrogen and might be remnants of former hot Jupiters.

estimated to be $\dot{M}_{\rm HI} \simeq 5.7 \times 10^{10}\,{\rm g\,s^{-1}}$ and $\dot{M}_{\rm H_2} \simeq 1.7 \times 10^{10}\,{\rm g\,s^{-1}}$ in Model A, $\dot{M}_{\rm HI} \simeq 1.3 \times 10^{11}\,{\rm g\,s^{-1}}$ and $\dot{M}_{\rm H_2} \simeq 3.5 \times 10^{9}\,{\rm g\,s^{-1}}$ in Model B, and $\dot{M}_{\rm HI} \simeq 5.2 \times 10^{11}\,{\rm g\,s^{-1}}$ in Model C, in agreement with the observational lower limit of $\sim 10^{10}\,{\rm g\,s^{-1}}$ (Vidal-Madjar et al. 2003). We obtain a life time (t_2) of 10^{10} to 10^{11} years. During 5×10^9 years, HD 209458b may have lost 1% to 7% of its initial mass.

With models of heat conduction within escaping atmospheres, Watson et al. (1981) showed that the escape rate can be limited by heat exchange. Using their result applied to HD 209458b, we found that the escape rate is heat-limited to $\sim 10^{12}\,{\rm g\,s^{-1}}$, in agreement with the results obtained by Trilling (1999) and Lammer et al. (2003). Although these results neglect the tidal forces, our values are below this limit and therefore do not need a full calculation of the heat exchange within the thermosphere.

At a given temperature, the escape rate is roughly proportional to the thermobase densities and the energy input. However, using the temperature calculated from the energy balance, the escape rate is less sensitive to the assumed input parameters. It is roughly proportional to the thermobase densities to the power of 0.3, and proportional to the energy input to the power of about 0.4.

6. Life time of hot Jupiters

Finally, we can also estimate the life time of a given planet as a function of its mass and orbital distance (Fig. 5). We conclude that planets with orbital distance lower than 0.03–0.04 AU (corresponding to orbital periods shorter than 2–3 days) have short life time unless they are significantly heavier than Jupiter. This may explain why only few planets have been detected with periods below 3 days. Low-mass hot Jupiters have also short life times, meaning that their nature must evolve with time. These planets must loose a large fraction of their hydrogen. This process can lead to planets with an hydrogen-poor atmosphere ("hot Neptunes"), or even with no more atmosphere at all. The emergence of planets modified by evaporation (and possibly the emergence of the inside core of former and evaporated hot Jupiters) may constitute a new class of planets (see also Trilling et al. 1998). If they exist, these planets could be called the "Chthonian" planets in reference to the Greek deities who come from hot infernal underground (Hébrard et al. 2003).

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