A&A 419, L13–L16 (2004)
DOI: 10.1051/0004-6361:20040129

Astronomy & Astrophysics

The effect of evaporation on the evolution of close-in giant planets

I. Baraffe[1], F. Selsis[2], G. Chabrier[1], T. S. Barman[3], F. Allard[1], P. H. Hauschildt[4], and H. Lammer[5]

[1] CRAL (UMR 5574 CNRS), École Normale Supérieure, 69364 Lyon Cedex 07, France
e-mail: `[ibaraffe; chabrier; fallard]@ens-lyon.fr`
[2] Centro de Astrobiología (INTA-CSIC), Ctra. de Ajalvir km 4, 28850 Torrejón de Ardoz, Madrid, Spain
e-mail: `selsis@obs.u-bordeaux1.fr`
[3] Department of Physics, Wichita State University, Wichita, KS 67260-0032, USA
e-mail: `travis.barman@wichita.edu`
[4] Hamburger Sternwarte, Gojenbergsweg 112, 21029 Hamburg, Germany
e-mail: `yeti@hs.uni-hamburg.de`
[5] Space Research Institute, Austrian Academy of Sciences, Schmieldstrasse 6, 8042 Graz, Austria
e-mail: `helmut.lammer@oeaw.ac.at`

Received 16 January 2004 / Accepted 4 April 2004

Abstract. We include the effect of evaporation in our evolutionary calculations of close-in giant planets, based on a recent model for thermal evaporation taking into account the XUV flux of the parent star (Lammer et al. 2003). Our analysis leads to the existence of a critical mass for a given orbital distance $m_{\rm crit}(a)$ below which the evaporation timescale becomes shorter than the thermal timescale of the planet. For planets with initial masses below $m_{\rm crit}$, evaporation leads to a rapid expansion of the outer layers and of the total planetary radius, speeding up the evaporation process. Consequently, the planet does not survive as long as estimated by a simple application of mass loss rates without following consistently its evolution. We find out that the transit planet HD 209458b might be in such a dramatic phase, although with an extremely small probability. As a consequence, we predict that, after a certain time, only planets above a value $m_{\rm crit}(a)$ should be present at an orbital distance a of a star. For planets with initial masses above $m_{\rm crit}$, evaporation does not affect the evolution of the radius with time.

Key words. planetary systems – stars: individual: HD 209458, OGLE-TR-56

1. Introduction

The increasing number of discovered giant planets orbiting at $\lesssim$0.1 AU from their parent star raises fundamental questions about their formation and migration process and about the influence of the parent star through irradiation or tidal effects. The recent discovery of an extended atmosphere for the transiting exoplanet HD 209458b (Vidal-Madjar et al. 2003) highlights the occurence of atmospheric evaporation for these close-in planets. Whether such evaporation due to heating from the incident stellar flux leads to major mass loss during the planet lifetime, and whether this process affects significantly the structure of the planet and thus its *m*-*R* relationship is an open question, which is of prime importance for our understanding of planetary system formation. New evaluations of atmospheric thermal evaporation rates by Lammer et al. (2003, L03), based on exospheric heating by stellar XUV radiation, yield significantly larger rates than the previous estimates assuming Jeans escape at the effective temperature of the planet. The first attempt of L03 to model such a complex process yields an escape rate in good agreement with the observational determinations of Vidal-Madjar et al. (2003) for HD 209458b, providing encouraging support for further exploration. Moreover, since stellar XUV fluxes vary significantly with time and can be order of magnitudes larger at very young ages, these evaporation rates are much larger at the planet early evolutionary stages. L03 thus suggest that mass loss could be an important event in the life of close-in exoplanets, contrarily to what was previously thought. It is the purpose of this letter to explore this issue by taking into account consistently the thermal escape rates of L03 along the evolution of strongly irradiated planets (Baraffe et al. 2003, hereafter B03). Since an important issue of this analysis is to determine whether evaporation affects significantly the inner structure and thus the *m*-*R* relationship of exoplanets, we focus on the case of presently detected transits, namely HD 209458b, with a = 0.046 AU (Charbonneau et al. 2000) and OGLE-TR-56b, with a = 0.023 AU (Konacki et al. 2003).

Send offprint requests to: I. Baraffe,
e-mail: `ibaraffe@ens-lyon.fr`

2. Description of the models

The evolutionary calculations are based on the consistent coupling between the irradiated atmospheric and interior structures as described in B03, and in Barman et al. (2001) for the atmosphere model calculations. Such a consistent treatment of the irradiated atmospheric structure and the internal, partially radiative structure successfully reproduces the observed parameters of the transit planet OGLE-TR-56b (Chabrier et al. 2004).

Details of the model used to derive thermal evaporation rates can be found in L03. The basic idea relies on the fact that the energy deposition by stellar XUV leads to exospheric temperatures higher than the blow-off temperature for H. Therefore, the classical Jeans' description of thermal escape must be replaced by a hydrodynamic modeling of the expansion and mass loss. The energy-limited atmospheric mass loss rate $\dot{M}$ can be written:

$$\dot{M} = 3\beta^3 F_\star/(G\rho), \qquad (1)$$

where β is the ratio between the expansion radius R_1, where the bulk of the XUV radiation is absorbed, and the planetary radius R_P and $\rho = (3m)/(4\pi R_\mathrm{P}^3)$ is the mean planet density. L03 estimate β by applying the hydrodynamic model of Watson et al. (1981). The term $F_\star$ is the stellar flux, averaged over the whole planet surface, taking into account both the contribution in the 1−1000 Å wavelength interval and the Lyman-α flux, so that the total contribution $F_\star$ for an orbital separation a (in AU) is $F_\star = (F_\mathrm{XUV}+F_\alpha)/a^2$. Although β is expected to vary with $F_\star$ and a, we fix it at the maximum value $\beta = 3$ found in L03, which is in good agreement with the observed expanded exosphere of HD 209458b (Vidal-Madjar et al. 2003). Estimates of XUV and Lyman-α fluxes and their time dependence are based on the current solar value and a collection of data for solar type stars covering an age from 100 Myr to 8 Gyr. As in L03, we adopt for the XUV and Lyman-α contributions:

$$\begin{cases} F_\mathrm{XUV}(t) = 6.13\, t^{-1.19} f_\mathrm{XUV} & \text{if } t \geq 0.1 \text{ Gyr}, \\ F_\mathrm{XUV}(t) = F_\mathrm{XUV}(0.1) & \text{if } t < 0.1 \text{ Gyr} \end{cases} \qquad (2)$$

$$\begin{cases} F_\alpha(t) = 3.17\, t^{-0.75} f_\alpha & \text{if } t \geq 0.1 \text{ Gyr}, \\ F_\alpha(t) = F_\alpha(0.1) & \text{if } t < 0.1 \text{ Gyr} \end{cases} \qquad (3)$$

where t is the age in Gyr, and $f_\mathrm{XUV} = 8.5\times10^{-4}$ W m^{-2} and $f_\alpha = 1.42\times10^{-3}$ W m^{-2} are respectively the Sun XUV and Lyman-α surface-averaged fluxes at 1 AU (Woods & Rottman 2002). Equations (2) and (3) recover the solar values for t = 4.5 Gyr.

3. Evolution of evaporating planets

We have implemented the evaporation rates given by Eq. (1) in our evolutionary code for irradiated planets, focusing on the two aforementioned orbital separations, a = 0.023 AU and a = 0.046 AU. We investigate planets with initial masses 0.5 M_J to 5 M_J, orbiting a solar type star ($T_{\mathrm{eff}\star}$ = 6000 K). For this mass range, evaporation rates vary from $\sim10^{-8}$ M_J/yr at young ages to $\sim10^{-12}$ M_J/yr for $t > 5$ Gyr.

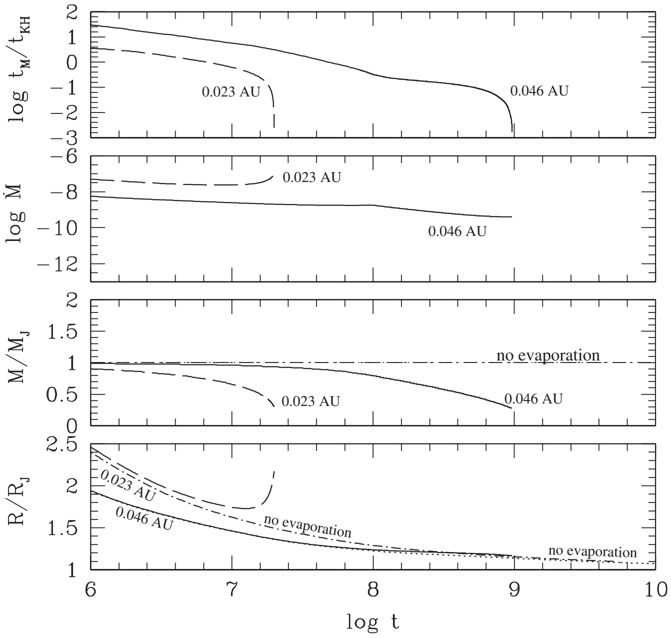

Fig. 1. Evolution of an evaporating planet with initial mass 1 M_J at different orbital separations. From lower to upper panel: the planet radius (in units of Jupiter radius $R_\mathrm{J} = 7.1492 \times 10^9$ cm), mass, evaporation rate $\dot{M}$ in M_J/yr and the ratio of the evaporation rate to thermal timescale $\log(t_{\dot{M}}/t_\mathrm{KH})$. The solid (with evaporation) and dotted (no evaporation, lower panels) curves correspond to a = 0.046 AU. The long-dashed (with evaporation) and dash-dotted (no evaporation, lower panels) curves correspond to a = 0.023 AU.

3.1. Response to mass loss: The case of a 1 M_J planet

Figure 1 shows the evolution of an evaporating planet with initial mass 1 M_J. A key quantity to understand the response of an object to mass loss is the ratio of the mass loss rate timescale $t_{\dot{M}} = m/\dot{M}$ to the thermal timescale, characterised by the Kelvin-Helmotz timescale $t_\mathrm{KH} \sim 2Gm^2/(RL)$. Such a ratio is displayed in the upper panel of Fig. 1. As long as $t_{\dot{M}}/t_\mathrm{KH} > 1$, the evolution of the planet radius $R(t)$ is barely affected by evaporation, as seen by the comparison between the non-evaporating and evaporating curves in the lower panel of Fig. 1 (see also Fig. 3). However, when $t_{\dot{M}}$ becomes shorter than t_KH, the evolution of the planet changes drastically: its mass decreases faster than its contracting radius. Consequently, m/R_P decreases increasingly rapidly with time, or conversely the planet mean density increases more and more slowly, compared to a case with slower evaporation. The evaporation rate thus decreases more slowly with time since $\dot{M} \propto 1/\rho \propto R_\mathrm{P}^3/m$ (Eq. (1)). Consequently, the ratio $t_{\dot{M}}/t_\mathrm{KH}$ keeps decreasing. When $t_{\dot{M}} \lesssim t_\mathrm{KH}/10$, the response of the planet becomes rather violent, as indicated by the sudden increase of the radius at $t \sim$ 20 Myr for the case a = 0.026 AU (Fig. 1, long-dashed curve). This stems from the fact that the outer layers start to expand significantly and the radius, instead of decreasing slowly or remaining constant, increases rapidly, yielding a sudden increase of the evaporation rate $\propto R_\mathrm{P}^3$, producing in turn further expansion of the outer layers. The situation turns into kind of a runaway behaviour and points to a catastrophic fate for the planet, at least concerning its hydrogen-rich envelope.

The expansion of the outer layers, yielding eventually such a violent reaction, can be understood in terms of entropy balance, in analogy with mass loss of low mass secondaries in compact binary systems (Ritter 1996). The entropy profile of an irradiated planet of mass m is constant throughout most of the structure. The outer layers, however, are radiative, and are characterized by a nearly isothermal, high entropy profile (Guillot et al. 1996; Barman et al. 2001; B03; Chabrier et al. 2004). The mass enclosed in the radiative layers is typically $\sim 10^{-5}\ M_{\rm J}$. With an evaporation rate $\dot{M} \sim 10^{-8}\ M_{\rm J}$/yr, it takes $\Delta t \sim 10^3$ yr to evaporate all these layers. The upper convective zones of entropy $S_{\rm conv}$ are then exposed to irradiation of the parent star, and become radiative with a significantly higher entropy $S_{\rm rad}$. In terms of gravothermal energy rate defined as:

$$\epsilon_{\rm grav} = -T\frac{\Delta S}{\Delta t} = -T\frac{(S_{\rm rad} - S_{\rm conv})}{\Delta t}, \qquad (4)$$

$\epsilon_{\rm grav}$ is thus negative. Gravothermal energy is thus released in the outer layers, and converted mainly into expansion work. At some time, this expansion work becomes significant compared with the (positive) gravothermal energy rate due to the planet contraction and cooling. This occurs when $t_{\rm KH} \gg t_{\dot{M}}$, yielding a runaway situation where evaporation is speeding up and leading eventually to a catastrophic event if other processes do not regulate the increase of R and $\dot{M}$. When a planet reaches such a critical regime, evaporation is speeding up drastically, at a much higher rate than expected from standard scenarios.

As seen in Fig. 1, $t_{\dot{M}} < t_{\rm KH}$ after 10 Myr for $a = 0.023$ AU and after 50 Myr for $a = 0.046$, respectively. The $a = 0.046$ sequence shown in Fig. 1 stops before showing a strong increase of R simply because it reaches the lower $T_{\rm eff}$-limit of our irradiated atmosphere grid, i.e. $T_{\rm eff} = 50$ K. The planet at $a = 0.046$ AU survives ~1 Gyr and the one at $a = 0.023$ AU only 20 Myr. Using the same evaporation rates without considering the effects on the evolution yields a time for complete evaporation of a 1 $M_{\rm J}$ planet of ~2 Gyr at $a = 0.046$ and ~40 Myr at $a = 0.023$ AU. A consistent treatment of evaporation and evolution, yielding the aforedescribed evaporation speeding up process, thus decreases appreciably, by a factor of ~2, the timescale of a planet for complete evaporation.

3.2. A critical mass for speeding up evaporation

Following the results of the previous section, we define a critical mass $m_{\rm crit}$ below which $t_{\dot{M}} = t_{\rm KH}/10$ is reached in <5 Gyr. A planet with initial mass $m < m_{\rm crit}$ orbiting a Sun-type star will thus evaporate entirely (or leave at least a rocky core) in less than 5 Gyr. Based on the present evaporation rates, we find that $m_{\rm crit} \sim 1.5\ M_{\rm J}$ for $a = 0.046$ AU and $m_{\rm crit} \sim 2.7\ M_J$ for $a = 0.023$ AU, as illustrated in Fig. 2. Note that in our calculations, evaporation starts at the very beginning of our evolutionary sequences. This is questionable, since heating from the parent star is likely to be smaller at the very early stages of the planet evolution, because either of the presence of a protoplanetary disk or the fact that the planet may form at a larger orbital distance and migrate inwards. Both processes have timescales obviously linked to the disk lifetime, with a reasonable upper limit of ~10 Myr (Strom et al. 1993; Armitage et al. 2003). On such short timescales, evaporation effects on the evolution of the planet are unsignificant in the presently considered mass range. Indeed, we checked that starting evaporation at an age $t \sim 10$ Myr does not change the fate of the planet and thus $m_{\rm crit}$. A prediction of the present calculations is thus the absence of exoplanets below the aforementioned critical masses and orbital distances after 5 Gyr.

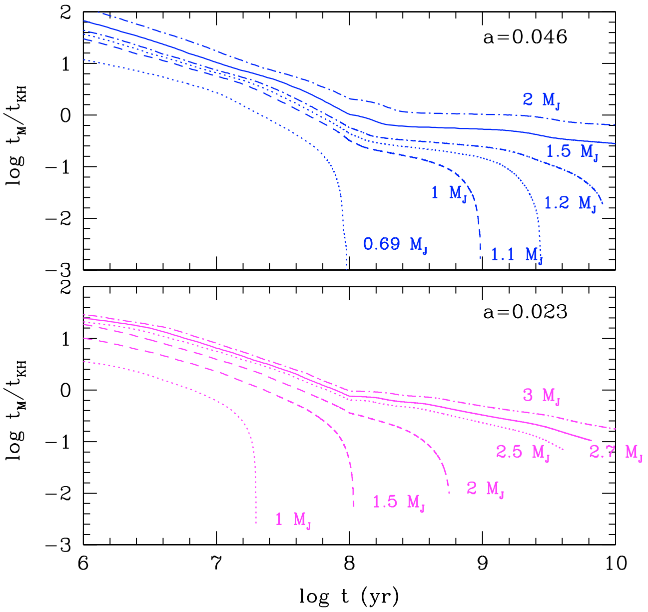

Fig. 2. Ratio of the mass loss timescale to thermal timescale $t_{\dot{M}}/t_{\rm KH}$ as a function of time (in yr) for planets with different initial masses, as indicated on the panels. Upper panel corresponds to orbital separation $a = 0.046$ AU and lower panel to $a = 0.023$ AU. In both panels, the solid curve indicates the critical mass below which $t_{\dot{M}}/t_{\rm KH} < 1/10$ in less than 5 Gyr (see text).

3.3. Evolution of the radius

For planets with initial mass $m \gtrsim m_{\rm crit}$, the evolution of the radius, $R(t)$, is barely distinguishable from non-evaporating cases. This is illustrated in Fig. 3 which portrays the evolution of a 2.7 $M_{\rm J}$ planet located at $a = 0.023$ AU from its parent star. With the present evaporation rates, the evaporating sequence (solid line) reaches a mass 1.5 $M_{\rm J}$ and a radius 1.12 $R_{\rm J}$ after 3 Gyr, in agreement with the observed properties of OGLE-TR-56B (Torres et al. 2003). The dashed curve shows the evolution of a non-evaporating planet of mass 1.5 $M_{\rm J}$, which reaches a similar radius 1.11 $R_{\rm J}$ at $t = 3$ Gyr. At such an age, the evaporation rate is $\sim 5.5 \times 10^{12}$ g s^{-1}, orders of magnitude larger than recent estimates of $\sim 10^3$ g s^{-1}, based on Jeans escape rates at exobase temperatures close to $T_{\rm eff}$ (Sasselov 2003).

Concerning the case of HD 209458b, we cannot find an evaporating sequence reproducing its properties. As for non-evaporating models (see B03), the predicted radius for the observed mass and inferred age of the system is about 25% smaller than the observed value. Interestingly enough, we find that a planet at $a = 0.046$ AU with initial mass ~1.1–1.2 $M_{\rm J}$ reaches the critical regime $t_{\dot{M}}/t_{\rm KH} < 0.1$ precisely at the age

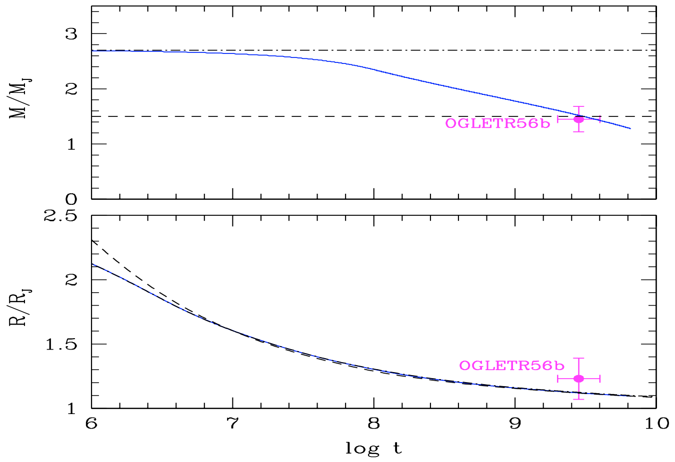

Fig. 3. Effect of evaporation on the radius and mass as a function of time (in yr) for planets at a = 0.023 AU from their parent star. The solid curve is an evaporating planet with initial mass 2.7 M_J, which reaches 1.5 M_J in 3 Gyr, reproducing the properties of OGLE-TR-56b (Torres et al. 2003). Comparison is made with non evaporating evolutionary sequences with mass 2.7 M_J (dash-dot) and 1.5 M_J (dash). Note that the solid and dash-dot curves are undistinguishable in the lower panel.

of HD 209458b ($\log t$ = 9.6–9.85) (see Fig. 2). Since our analysis suggests a violent reaction of a planet when reaching this regime, with rapid expansion of the outer layers (see Fig. 1), we may wonder whether HD 209458b is not in such a regime. Although the probability to see a transit planet in this rapid phase is very small, the discovery of other similar systems with unexplained large radii would suggest further attention to this scenario.

4. Conclusion

The present calculations, including a consistent treatment of irradiation and evaporation due to XUV/Lyman-α irradiation during the evolution of irradiated planets, suggest the existence of a critical mass $m_{\rm crit}$, which varies with orbital separations, below which the evaporation timescale becomes significantly shorter than the thermal timescale of the planet. Based on the present evaporation rates for solar conditions, we get $m_{\rm crit} \sim 1.5\ M_J$ at a = 0.046 AU and $m_{\rm crit} \sim 2.7\ M_J$ at a = 0.023 AU. For objects with mass below this critical mass, we find that: (i) the planet will evaporate entirely (except possibly for the central rocky core) within about 5 Gyr; (ii) its lifetime is shortened by a factor ~2 compared with the time predicted for complete evaporation but omitting the effect on the evolution; (iii) its outer layers expand rapidly and its radius eventually increases at some time; (iv) the planet undergoes a phase of rapid mass loss which could expel part or all of its remaining hydrogen-rich envelope in a very short timescale. Planets with initial masses $m_i > m_{\rm crit}$ survive to evaporation on a lifetime longer than 5 Gyr, and evolution is similar to the case of a non-evaporating irradiated planet. The values of $m_{\rm crit}$ depend on the evaporation rates which are still very uncertain and rely on a rather primitive model for such a complex process. Moreover, applying evaporation rates determined at the exosphere to the photospheric surface of the planet, the relevant boundary for evolution, is an extreme simplification. Uncertainties on the mass loss rates, however, do not affect the qualitative existence of a planet critical mass, for a given orbital distance, below which a planet eventually will react violently to evaporation and will expand again, possibly until complete evaporation. Such a behavior bears important consequences on the lifetime of close-in planets and on our understanding of their mass-orbital period distribution. Our results thus provide an excellent motivation to pursue efforts to understand evaporation effects and to explore further the influence of the high energy part of the parent star incident flux.

References

Armitage, P., Cathie, J., & Palla, F. 2003, MNRAS, 342, 1139

Baraffe, I., Chabrier, G., Barman, T., Allard, F., & Hauschildt, P. H. 2003, A&A, 402, 701 (B03)

Barman, T., Hauschildt, P. H., & Allard, F. 2001, ApJ, 556, 885

Chabrier, G., Barman, T., Baraffe, I., Allard, F., & Hauschildt, P. 2004, ApJ, 603, L53

Charbonneau, D., Brown, T., Latham, D., & Mayor, M. 2000, ApJ, 529, L45

Guillot, T., Burrows, A., Hubbard, W. B., Lunine, J. I., & Saumon, D. 1996, ApJ, 459L

Konacki, M., Torres, G., Jha, S., & Sasselov, D. 2003, Nature, 421, 507

Lammer, H., Selsis, F., Ribas, I., et al. 2003, ApJ, 598, L121 (L03)

Ritter, H. 1996, in Evolutionary Processes in Binary Stars (Dordrecht: Kluwer), NATO ASI Ser., 477, 223

Torres, G., Konacki, M., Sasselov, D., & Jha, S. 2003, ApJL, submitted `[arXiv:astro-ph/0310114]`

Sasselov, D. 2003, ApJ, 596, 1327

Strom, S., Edwards, S., & Skrutskie, M. 1993, in Protostars and planets III, 837

Vidal-Madjar, A., Lecavalier des Etangs, A., Désert, J.-M., et al. 2003, Nature, 422, 143

Watson, A., Donahue, T., & Walker, J. 1981, Icarus, 48, 150

Woods, T. N., & Rottman, G. J. 2002, in Atmospheres in the Solar System: Comparative Aeronomy, Geophysical Monograph 130, AGU, 221