Introduction The upper atmospheres of short periodic exoplanets are affected strongly by the stellar X-ray and EUV (XUV) radiation and plasma environment (Schneider et al. 1998). Therefore, these bodies should experience high thermal (Lammer et al. 2003; Levasseur-Regourd et al. 2004; Yelle 2004; Vidal Madjar et al. 2003; Baraffe et al. 2004; Tian et al. 2005; Erkaev et al. 2006; Penz et al. 2006) and non-thermal (Erkaev et al. 2003; Khodachenko et al. 2006) mass loss. Khodachenko et al. (2006) studied the minimum and maximum possible atmospheric erosion of the “Hot Jupiter” HD209458b due to Coronal Mass Ejections (CMEs) and found that this exoplanet, which orbits a solar-like star at 0.046 AU, could have been eroded to its core-mass if its atmosphere were not protected by a strong magnetic field. Because the mass loss depends on the strength of planetary magnetic fields, which are estimated for slow rotating tidally locked “Hot Jupiters” to be in a range of 0.005−0.1 $M_{Jup}$ (Grießmeier et al. 2004), weakly magnetized short periodic gas giants can experience large non-thermal mass loss rates during their whole life time. The aim of this paper is to determine at which distances exoplanets can maintain their initial mass, and where close orbit gas giants can experience huge mass loss rates that may influence the short period CoRoT-planet population.

1. Exosphere-formation and the onset of planetary mass loss

The overall evolution of a planet can be split into (1), the formation period during which the planet is formed and its mass grows, and (2), the mature period with the planet detached from gas reservoirs and exposed to loss processes driven by its host star. During the formation period the planet is in contact with a mass reservoir having certain pressure: the protoplanetary nebula. During an isolated period planets are surrounded by vacuum with no continuum pressure and an exosphere as the interface. The overall mass history of a planet is thus determined by pressure gradients as long as there is a nebula pressure and by exosphere properties once there is no nebula pressure.

The formation of the exosphere separates these two eras and the regimes of early mass-gain from the nebula and the long period of particle loss processes. An exosphere exists if there is a layer in an atmosphere or generally in a gas sphere where the mean free path of the particles is sufficiently large to allow them to escape from a planet. Protoplanets fill their Roche-lobe because that is where they are in contact with the nebula. For a small planet/star mass-ratio the size of the Roche lobe can be well approximated by the Hill-radius, $R_{Hill} = d(M_{pl}/[3M_{star}])^{1/3}$, where $d$ is the orbital distance. Equating this to the mean free path for hydrogen and assuming $P = nkT$ we obtain an exosphere formation pressure $P_{exo-form}$ at the Hill-sphere boundary

$$P_{exo-form} = \frac{kT}{d\sigma_H} \left(\frac{3M_{star}}{M_{pl}}\right)^{1/3},$$

(1)

where $\sigma_H$ is the hydrogen collision cross section. Assuming an exponential decay of the nebula pressure, $P_0$ with a time-scale $\tau_{neb}$, we calculate the time it takes for the lowest pressure around the planet to reach $P_{exo-form}$ and an exosphere to form within the Hill-sphere

$$t_{exo-form} = \tau_{neb} \ln \frac{P_0}{P_{exo-form}}.$$

(2)

We take $\sigma_H = \pi a_0^2$ with the Bohr-radius, $a_0$ as a lower limit for collisions under typical nebula-conditions. For typical nebula pressures and temperatures at the planet formation time, taken from the predicted CoRoT-planet population (Wuchterl et al. 2006), we arrive at $t_{exo-form} \approx 30 - \tau_{neb}$. With a typical global $\tau_{neb}$ of $\sim 10$ Myr representing a compromise between various empirical methods ($\tau_{neb} \sim 1 - 100$ Myr) (see Hillenbrand et al. 2005 for a recent update focused on dust IR-emission), one obtains average exosphere formation-times, $t_{exo-form} \approx 50 - 300$ Myr. Thus exospheres may form at significant ages after the planets’ host star arrived at the Zero-Age-Main Sequence (ZAMS).

2. Thermal mass loss

In order to study the evolution of the maximum possible thermal hydrogen loss rates from close-in Exosolar Giant Planets in a mass range of $10^{29}$ g (EGP I) to $10^{30}$ g (EGP II) at different orbital distances we estimate the thermal mass loss from the evolution of the XUV flux which arrives from the host star at the planet’s orbit. We use in the present study a scaling law derived from XUV flux observations of solar-like G stars with different age $\Phi_{XUV} = \frac{6.13r^{-1.9}}{f_{XUV}\text{}}$ (Ribas et al. 2005), where $r$ is the age of the star in Gyr, while $f_{XUV} \approx 8.5 \times 10^{-4}$ W m$^{-2}$ is the flux at 1 AU averaged over the planetary sphere. It is scaled to the different orbital distances by using an $r^{-2}$ dependency. The maximum possible thermal mass loss rate $\Gamma_\text{th}$ can be calculated by assuming that an atmosphere contains no efficient IR-cooling molecules and by using the energy-limited equation which was originally derived for Earth-like planets by Watson et al. (1981). Recently, Erkaev et al. (2006) modified the energy-limited equation for the application to “Hot Jupiters”

$$\Gamma_{\text{th}} = \frac{4\pi P_\text{r} f_{XUV} \Phi_{XUV}}{m M_\text{pl} G K},$$

(3)

where $P_r$ and $M_pl$ are the planetary radius and mass, $K$ is a factor which is related to the Roche-lobe effect (Erkaev et al. 2006) and is $\approx 0.5$ for the considered planet. $r_{XUV}$ is the distance in the thermosphere where the optical thickness $\tau_{XUV} \rightarrow 1$ and the main part of the XUV radiation is absorbed. One should note that $r_{XUV}$ is much closer to the planetary radius $R_p$ than the distance used by Watson (1981). By using Eq. (3) with $r_{XUV} \approx 1.3 R_p$ (Yelle 2004) we can calculate the maximum expected thermal mass loss rate for HD209458b ($R_p = 1.43 R_{Jup}$, $M_pl = 0.69 M_{Jup}$) at present time. It is $\sim 1.7 \times 10^{11}$ g s$^{-1}$ and appears to be in good agreement with Vidal-Madjar et al. (2003), Yelle (2004) and Tian et al. (2005). The mass loss rate for HD209458b at about 200 Myr after its host star arrived at the ZAMS is $\sim 6.0 \times 10^{11}$ g s$^{-1}$. We note that Lammer et al. (2003) applied Watson’s assumption for “Hot Jupiters” and overestimated the energy-limited loss rate by an order of magnitude. One can see from Table 1 that thermal evaporation may be an efficient loss process for close-in gas giants at $d < 0.05$ AU with $M_pl < 5 \times 10^{25}$ g ($< 0.25 M_{Jup}$ and exosphere formation times $\leq 200$ Myr. If one proceeds to longer exosphere formation times the integrated mass loss is gradually decreasing. At larger orbital distances, the thermal mass loss is $\leq 1 \%$. Thermal evaporation from close-in lower mass exoplanets may be strong enough to remove their hydrogen envelopes from their cores. One should also note that exoplanets with orbits $< 0.02$ AU will experience an even higher thermal mass loss due to the higher XUV flux and the mass loss enhancement due to the Roche-lobe effect (Erkaev et al. 2006).
Table 1. Thermal mass loss in % of the initial planetary mass of EGP I and EGP II integrated over the history of the stellar system for a representative exosphere formation time $t_{\text{exo-form}} \approx 200$ Myr.

| d [AU] | P [d] | EGP I: $L_{\text{th}}$ [%] | EGP II: $L_{\text{th}}$ [%] |
|--------|-------|---------------------------|---------------------------|
| 0.02   | 1     | $\sim 87$                 | $\sim 87$                 |
| 0.05   | 4     | $\sim 14$                 | $\sim 14$                 |
| 0.013  | 16    | $\sim 2$                  | $\sim 2$                  |

Table 2. Maximum CME-induced H$^+$ pick up ion mass loss rates per CME collision for “Hot Jupiters” with different substellar planetary magnetopause obstacles as a function of orbital distance.

| d [AU] | P [d] | Obstacle $\times R_{\text{pl}}$ | $\Gamma_{\text{CME}}$ [g s$^{-1}$] |
|--------|-------|---------------------------------|-----------------------------------|
| 0.02   | 1.0   | 1.5                             | $2.8 \times 10^{-4}$             |
| 0.02   | 1.0   | 2.0                             | $3.8 \times 10^{-3}$             |
| 0.05   | 4.0   | 1.3                             | $10^{-4}$                         |
| 0.05   | 4.0   | 1.5                             | $2.0 \times 10^{-3}$             |
| 0.05   | 4.0   | 2.0                             | $2.7 \times 10^{-2}$             |
| 0.013  | 16.0  | 1.3                             | $\times 10^{-4}$                 |
| 0.013  | 16.0  | 1.5                             | $1.5 \times 10^{-2}$             |
| 0.013  | 16.0  | 2.0                             | $3 \times 10^{-1}$               |

3. CME-induced nonthermal mass loss

Taking into account that tidal-locking of short periodic exoplanets may result in weaker planetary magnetic moments, as compared to fast rotating Jupiter-class planets at larger orbital distances (Grießmeier et al., 2004), Khodachenko et al. (2006) found that the encountering CME plasma may compress the magnetosphere and force the magnetospheric standoff distance down to heights where ionization and ion pick-up of the planetary neutral atmosphere by the CMEs plasma flow takes place. Assuming for the G-type host star of HD209458b the average CME occurrence rate as the one observed on the Sun, Khodachenko et al. (2006) found that, depending on magnetic protection “Hot Jupiters” at 0.045 AU could have lost over their lifetime a mass from 2 % up to more than $M_\text{up}$. For estimating the orbital distance at which Jupiter-class exoplanets maintain the main part of their initial mass, we calculate the “maximum” possible CME-induced mass loss between orbital distances of 0.015 – 0.2 AU.

In the case of our Sun the maximum expected CME plasma density $n_{\text{CME}}$ at orbital distances $\leq 0.2$ AU is estimated from the analysis of CME associated brightness enhancements in the white-light coronagraph images. By using an analogy between the Sun and solar-type stars the maximum CME density dependence on the orbital distance $d$ from the star can be assumed as a power-law (e.g., Khodachenko 2006, and references therein) $n_{\text{CME}}(d) = n_0(d/d_0)^{-3.6}$, which for $d_0 = 5 \times 10^3$–$5 \times 10^6$ cm$^{-3}$ and $d_0 = 3R_{\text{Sun}}$ gives a good approximation for the values estimated from the SOHO/LASCO coronagraph images. The average mass of CMEs, $M_{\text{CME}}$, is $\approx 10^{15}$ g and the average duration of CMEs, $t_{\text{CME}}$, at distances $(6-10)R_{\text{Sun}}$ is $\approx 8$ h. The collision rate between CMEs and “Hot Jupiters” can be estimated by Khodachenko et al. (2006)

$$f_{\text{col}} = \frac{(\Delta_{\text{CME}} + \delta_p) \sin(\Delta_{\text{CME}} + \delta_p)/2}{2 \pi \sin \Theta \Delta_{\text{CME}}} \times \frac{f_{\text{CME}}}{f_{\text{CME}}},$$

where $f_{\text{CME}}$ is the CME occurrence rate, $\Delta_{\text{CME}}$ and $\delta_p$ are the CME and planetary angular sizes, $\Theta$ is the latitude distribution of CME producing regions. Assuming an average stellar CME occurrence rate $f_{\text{CME}}$ of $\sim 3$ CMEs per day (Khodachenko et al. 2006; and references therein), and taking the size, duration and latitude distribution of CMEs close to the solar ones ($\Delta_{\text{CME}} = \pi/4$ to $\pi/3$, $t_{\text{CME}} = 8$ h, $\Theta = \pi/3$), with the angular size $\delta_p$ related to the orbital distance between 0.015–0.2 AU of 0.045–0.0034 rad, one obtains a CME collision rate $f_{\text{col}}$ of $\sim 0.17$–0.3 hits per day. Using these values an average total CME exposure time $t_{\text{CME}} \approx 1.2 \times 10^{10}$ s during a period of 5 Gyr is obtained.

To calculate atmospheric erosion rates we apply the same time-dependent numerical algorithm, which is able to solve the system of hydrodynamic equations through the transonic point for calculation of the upper atmospheric hydrogen density as used by Khodachenko et al. (2006) and Penz et al. (2006).

The obtained density profiles are in agreement with the density profiles calculated by Yelle (2004) and Tian et al. (2005). For studying the expected maximum possible atmospheric erosion due to CMEs we assume magnetospheres which build obstacles against the CME plasma flow at substellar distances of 1.3, 1.5 and 2.0 $R_{\text{pl}}$. For the CME-induced H$^+$ pick-up loss rates caused by the CME plasma flow we take into account the ionization processes produced by CMEs during the interaction with the neutral atmosphere above the assumed planetary obstacles. The H$^+$ pick-up loss calculations are performed with a numerical test particle model which was successfully used for the simulation of ion pick-up loss rates from various planetary atmospheres (Lichtenegger et al. 1995; Erkaev et al. 2005; Khodachenko et al. 2006). The calculation of the particle fluxes is performed by dividing the space above and around the planetary obstacle onto a number of volume elements $\Delta V$. Production rates of planetary H$^+$ ions are obtained by calculation of the CME plasma flow absorption along streamlines due to charge exchange, photo-ionization, and electron impact ionization with the extended upper atmosphere. The CME plasma flux $\Phi_{\text{CME}}$ in a volume element $\Delta V$ at a given position $r_i$ with respect to the planetary center is determined by

$$\Phi_{\text{CME}}(r_i) = \Phi_{\text{CME}}^{(0)}(r_i) e^{-\int_0^r \frac{1}{\sigma_{\text{H}^+} ds}},$$

where the integration is performed from the upstream CME plasma flow to the corresponding point $s_i$ at position $r_i$ on the streamline. $\Phi_{\text{CME}}^{(0)}$ is the unperturbed CME plasma flux, $n_{\text{H}}$ is the neutral hydrogen density as a function of planetary distance, $\sigma_{\text{H}^+}$ is the energy dependent cross section of hydrogen ionization processes, and $ds$ is the line element along the streamline. The total planetary ion production rate from atmospheric hydrogen atoms in each volume element can be written as the sum $p_{\text{H}^+}^i = p_{\text{H}^+}^{\text{ce}} + p_{\text{H}^+}^{\text{ei}} + p_{\text{H}^+}^{\text{gi}}$, with $p_{\text{H}^+}^{\text{ce}}$, the electron impact ionization, $p_{\text{H}^+}^{\text{ei}}$, the charge exchange rate, and $p_{\text{H}^+}^{\text{gi}}$, the photo-ionization rate. The total H$^+$ ion mass loss rate finally becomes

$$\Gamma_{\text{CME}} = \sum_i p_{\text{H}^+}^i \Delta V m_{\text{H}^+}.$$
Fig. 1. Residual mass after 5 Gyr exposure of dense CMEs in units of $M_{\text{up}}$ of weakly magnetized “Hot Jupiters” as a function of orbital distance compared with planetary obstacles at 1.3 $R_{\text{pl}}$ (solid line), 1.5 $R_{\text{pl}}$ (dashed line), and 2.0 $R_{\text{pl}}$ (dotted line). The horizontal dashed-dotted lines indicate the masses of Saturn, Uranus, Neptune, the horizontal dotted lines corresponds to the mass of the Earth (lower line) and to the “Super-Earth” ($M_{\text{pl}} \approx 10M_{\text{Earth}}$) mass domain (upper line), and the black circles show the so far observed lower mass close-in exoplanets.

of orbital distance compared to 5 known low-mass exoplanets (Gliese 876d, 55 Cnc e, HD69830b, HD160691d, HD69830c) (http://exoplanet.eu/catalog.php). The results obtained from the numerical ion pick up test particle model simulations indicate that weakly magnetized gas giants at orbital distances $\leq 0.05$ AU or periods $\leq 4$ days may lose a mass equivalent to that of Jupiter during a 5 Gyr time period. By comparing the results of the integrated CME-induced mass loss with the thermal evaporation loss shown in Table 1, one can see that for magnetically unprotected planets nonthermal loss processes are much more efficient than thermal evaporation.

Baraffe et al. (2004) compared the ratio of the mass loss timescale $t_{\text{M}}$ to the thermal timescale $t_{\text{th}}$, which is characterized by the Kelvin-Helmoltz timescale, found that, when $t_{\text{M}}/t_{\text{th}}$ becomes $< 1$ the evolution of the “Hot Jupiter” changes drastically which results in rapid expansion of the planetary radius and enhances the mass loss. Depending on the strength of the planetary magnetic field, XUV flux and exosphere formation time, close-in gas giants at orbital distances $\leq 0.05$ AU may experience this violent mass loss effect.

One can also see from Fig. 1 that it is very unlikely that the three low mass exoplanets HD69830b, HD160691d, and HD69830c are remaining cores of eroded gas giants. They could have lost their hydrogen-envelopes but their initial mass was not much larger than that of Neptune. The two other low mass exoplanets Gliese 876d and 55 Cnc e are located at orbital distances where they could have been strongly affected by mass loss. Therefore, both exoplanets can be remaining cores of eroded weakly magnetized gas giants.

4. Conclusions

Our study indicates that mass loss of weakly magnetized short periodic “Hot Jupiters” can produce the observed masses of Gliese 876d and 55 Cnc e, while the three other known lower mass close-in exoplanets HD69830b, HD160691d and HD69830c belonged most likely since their origin to the Neptune-mass domain. The results of our study indicate that only a combination of the size detection with CoRoT and ground-based follow-up mass determinations together with theoretical mass loss studies over the exoplanets’ history can bring reliable information on the statistics of remaining cores, shrunken gas giants and “unaffected” lower mass exoplanets, like Super Earths or Ocean planets. Furthermore, thermal evaporation from “Hot Jupiters” at orbits $< 0.02$ AU, together with CME-triggered nonthermal mass loss processes and tidal interactions (Patzold and Rauer [2002]) can be a reason that so far no “Hot Jupiter” is observed at these close distances to its host star.

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