*"Physics of Auroral Phenomena", Proc. XXX Annual Seminar, Apatity, pp. 177 - 180, 2007*

Polar Geophysical Institute

# EVAPORATION OF CLOSE-IN GIANT PLANETS DUE TO INTENSE XUV RADIATION

T. Penz[1], N.V. Erkaev[2], Yu.N. Kulikov[3], H. Lammer[4], G. Micela[1], D. Langmayr[4], H.K. Biernat[4]

[1]*INAF - Osservatorio Astronomico di Palermo, Palermo, Italy*
[2]*Institute for Computational Modelling, Russian Academy of Sciences, Krasnoyarsk, Russian Federation*
[3]*Polar Geophysical Institute, Russian Academy of Sciences, Murmansk, Russian Federation*
[4]*Space Research Institute, Austrian Academy of Sciences, Graz, Austria*

**Abstract.** Astrophysical observations of young stars indicate much larger X-ray and EUV fluxes than stars with the age of our present Sun. Because of this one can expect that during and after giant planet formation the early high radiation flux of a parent star in the short wavelengths will have great impact on atmospheric loss from such a planet . We solve the system of hydrodynamic equations for a hydrogen atmosphere to study thermal escape processes from a "Hot Jupiter". It is shown that HD209458b might have lost about 4 % of its present mass due to thermal atmospheric escape.

## 1. Introduction

The Hot Jupiter HD209458b which orbits around an about 4 Gyr old solar-like G star was the first exoplanet for which several transits across the stellar disk have been observed (Charbonneau et al., 2000) indicating that its visual radius is only slightly larger than Jupiter's of about 1.32 $R_{jup}$ (Knutsen et al., 2007). Charbonneau et al. (2002) observed HD209458b's dense lower atmosphere and detected neutral Na due to absorption in the NaI D lines. The spectroscopic observations in the absorption NaI D lines and H Lyman-α line during transits provided the first opportunity to constrain the structure of the atmosphere of a Hot Jupiter. The size of the planet inferred from the H Lyman-α absorption corresponds to atomic hydrogen density of at least $10^6$ $cm^{-3}$ at a planetary distance of about 2.5 $R_{pl}$ (Vidal-Madjar et al., 2003). Vidal-Madjar et al. (2003) concluded from their observations that atomic hydrogen escapes from the extended upper atmosphere of HD209458b with a rate of $> 10^{10}$ g/s.. These results can be interpreted as an observational evidence of the existance at an upper atmosphere which experiences hydrodynamic blow-off conditions. Because of the high X-ray and EUV (XUV) flux of a close host star, the upper atmospheres of short-periodic hydrogen-rich gas giants can be heated to temperatures of more than 10000 K.

Lammer et al. (2003) applied a scaling method for the estimation of the exospheric temperature of Hot Jupiters and found that exospheric temperatures can easily reach values of more than 10000 K at orbital distances < 0.1 AU, if efficient cooling by IR-irradiating molecules like $H_3^+$ is neglected. Yelle (2004, 2006) applied 1-D hydrodynamic calculations of the atmospheric structure of Hot Jupiters in orbits with semi-major axes from 0.01-0.1 AU and found a hydrogen loss rate of about 4.6 x $10^{10}$ g/s. In agreement with Lammer at al. (2003), this study showed that the thermospheres of short-periodic gas giants may be heated to temperatures up to about 10000 K by the XUV flux from the central star. Observational evidence of XUV heating within the lower thermosphere of HD209458b was recently provided by Ballester et al. (2007) who detected a 0.03 % Balmer-continuum absorption. Tian et al. (2005) developed a numerical model which solves the time-dependent hydrodynamic equations of mass, momentum and energy balance, by using a Chapman-like 2-D energy deposition function and applied it to HD209458b. These authors found a maximum loss rate of about 6 x $10^{10}$ g /s which is in agreement with that of Yelle (2006). Recently, Garcia Munoz (2007) presented a more detailed model, giving similar results as the previous ones.

An important point which was neglected in previous studies of Yelle (2004) and Tian et al. (2005) is the fact that for close-in gas giants, the L1 point is located somewhere in the expanded atmosphere and might be even below the exobase (Lecavelier des Etangs et al., 2004; Erkaev et al., 2007; Lecavelier des Etangs, 2007, Garcia Munoz, 2007). The Roche lobe is defined as a volume of space around a planet where its atmosphere is gravitationally bound to that planet. For HD209458b, the L1 point is at about 4.3 $R_{pl}$ (Erkaev et al., 2007) and the exobase is above or near the Roche lobe, all particles reaching the L1 point are lost automatically.

In order to study evolutionary aspects of extrasolar giant planet atmospheres, it is necessary to consider also the much higher XUV fluxes of younger stars (e.g., Ribas et al., 2005). Previous investigations of evolutionary effects of evaporating Hot Jupiters like HD209458b by Lammer et al. (2003) and Baraffe et al. (2004) were based on the energy-limited approach, which have overestimated the thermal mass loss rates during evolutionary important early time periods. Lecavalier des Etangs (2007) proposed recently an approach for a fast estimation of the escape rates over the life time of the discovered ``Hot Jupiters''.

In contrast to the previous studies which focused on evolutionary aspects of ``Hot Jupiters'' by Lammer et al. (2003), Baraffe et al. (2004) and Lecavlier des

Etangs (2007), this study has the aim to investigate the evolution of the mass loss by using a detailed 1-D time-dependent hydrodynamic model.

## 2. Model description

We model the hydrodynamic conditions for a hydrogen-rich atmosphere of Hot Jupiters by applying the set of the 1-D fluid equations for mass, momentum and energy conservation in spherical coordinates

$$\frac{\partial n}{\partial t} + \frac{1}{r^2}\frac{\partial n v r^2}{\partial r} = 0,$$

$$n\frac{\partial v}{\partial t} + nv\frac{\partial v}{\partial r} + \frac{1}{m}\frac{\partial p}{\partial r} = nF_{grav},$$

$$nm\left(\frac{\partial E}{\partial t} + v\frac{\partial E}{\partial r}\right) = q - p\frac{1}{r^2}\frac{\partial r^2 v}{\partial r} + \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\chi\frac{\partial T}{\partial r}\right),$$

Here, $n$ refers to the particle number density, $v$ is the velocity of the fluid, $m$ is the mass of a hydrogen atom, $p$ is the thermal pressure, $E$ is the total energy density, $q$ is the XUV volume heating rate, $T$ is the temperature of the atmospheric gas, and $\chi$ is the heat conductance. Also included are gravitational effects, referred to as Roche lobe effects by using

$$F_{grav} = -\frac{GM_{\rm pl}}{r^2} + \frac{GM_{\rm st}}{(d-r)^2} - \frac{G(M_{\rm st}-M_{\rm pl})}{d^3}(s-r),$$

where $G$ is the gravitational constant, $M_{pl}$ is the planetary mass, $M_{st}$ is the stellar mass, $d$ is the orbital distance of the planet, and $s$ is distance of the center of mass of the system from the planets center.
In the present stage of our investigations we introduce an idealized heating function. The stellar XUV radiation intensity $J$ decreases towards the exoplanet due to absorption in the thermosphere, which results in dissociation and ionization and, hence, in heating of the upper atmosphere according to

$$q = \eta\sigma n^* J = \eta(\sigma n_0 J_\infty)\tilde{n}\left(\frac{J}{J_\infty}\right)\exp\left(-\kappa\int_1^{\tilde{r}}(J/J_\infty)d\tilde{r}\right),$$

where $\sigma$ is the ionisation cross section for hydrogen. The evolution of the XUV flux is calculated from the scaling law (Baraffe et al., 2004; Ribas et al., 2005)

where $t$ is the age of the system in Gyr, while $f_{XUV}$ = 420 erg/cm$^2$/s is scaled from the value given in

$$F_{XUV} = 6.13t^{-1.19}f_{XUV} \qquad \text{for} \quad t \geq 0.1\text{Gyr},$$

Baraffe et al. (2004) to the orbit of HD209458b. The results should be considered as the behavior of an average G-type star.

## 3. Modelling of hydrogen loss rates for HD209458b

For studying the effect of thermal evaporation during the history of HD209458b we apply our model first to the present stellar condition.
Fig. 1 shows the flow velocity and number density for the present time XUV radiation value for 10 and 60 % heating efficiency η without (solid lines) and with (dashed lines) IR-cooling. The corresponding flow velocity at the L1 point for high and low η is in the order of about 7 km/s.

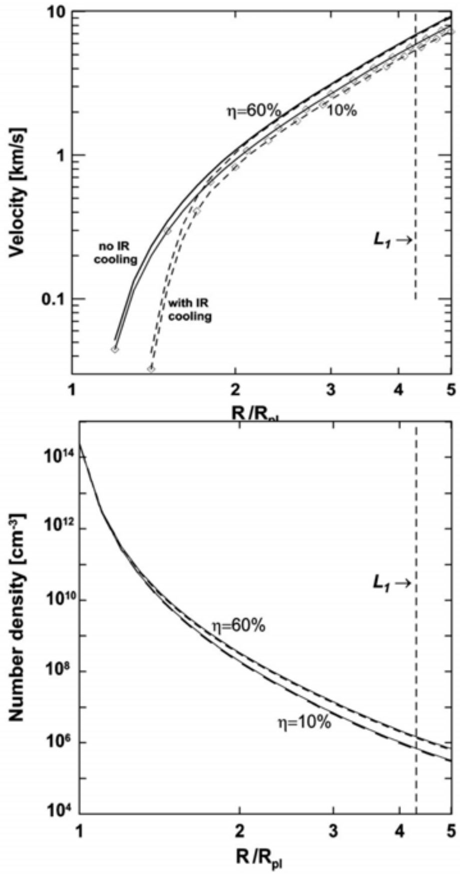


**Fig.1:** Profiles for the flow velocity (upper panel) and the density (lower panel) for present time XUV radiation level and heating efficiency of 10% and 60%.

Assuming a similar hydrogen density than Yelle (2004) at the lower boundary of the thermosphere n = 3 x $10^{14}$ cm$^{-3}$ we obtain the number density profile as a function of distance for present day HD209458b shown in the lower panel of Fig. 1. By using this initial condition we achieve a density of about $10^7$ cm$^{-3}$ at 3.0 R$_{pl}$ and at the L1 point, a density of about $10^6$ cm$^{-3}$ (η = 60 %). As one can see in Fig. 2, if we use a lower heating efficiency we obtain slightly lower densities at the similar distances. The obtained values are in agreement with the observations of Vidal-Madjar et al. (2003; 2004).The loss rate for the present day case therefore varies between 1-7 x $10^{10}$ g/s, in agreement with other hydrodynamic models.

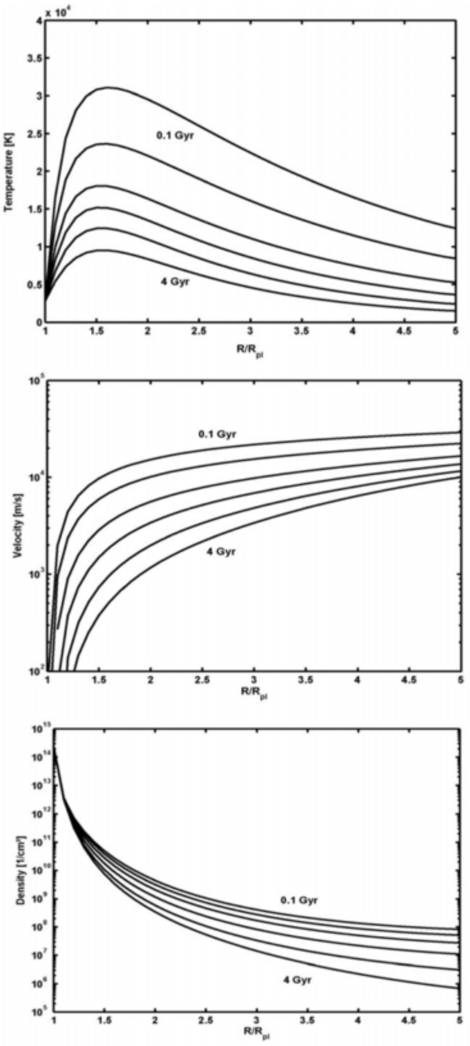


**Fig.2:** Profiles for the temperature (upper panel), the flow velocity (middle panel), and the density(lower panel). The profiles represent different XUV radiation levels corresponding to 4, 2, 1, 0.5, 0.2, and 0.1 Gyr.

For studying the loss rates of HD209458b over evolutionary time periods, we varied the volume heating rate *q* related to the evolving XUV flux of the host star, which could have been about 100 times larger after its arrival to the ZAMS than the present value (Ribas et al., 2005). Fig. 2 shows our model results for η = 60 % for density, temperature, and velocity profiles as a function of distance normalized to the planetary radii for ages of HD209458b's host star ranging from 0.1-4 Gyr. As
expected, the values for all hydrodynamic quantities increase with decreasing age of the system.
The obtained mass loss rate rises for η = 60 % from about 7 x 1010 g/s at present time (4 Gyr) up to about 1.6 x 1011 g/s 2 Gyr ago. At 0.5 Gyr the loss rate reaches 7.3 x 1011 g/s, and finally reaching more than 3 x 1012 g/s at 0.1 Gyr after the star arrived at the ZAMS. Integration of the hydrogen mass loss rate over HD209458b's life time of about 4 Gyr gives a total loss of about 4.5 x 1028 g for a high heating efficiency of 60 %, which is about 3.4 % of the total mass of the present planet. This indicates that even for high XUV fluxes during the early stages of the planetary evolution and an assumed high heating efficiency, HD209458b did not lose a significant part of its mass due to thermal evaporation. For lower values for the heating efficiency, the loss rates are about 2.6 x 1028 g or about 2 % of HD209458b's mass (η = 30\%), and 8 x 1027 g or < 1 % of HD209458b's mass for η = 10 %.

## 4. Conclusion

We apply a numerical 1-D time-dependent hydrodynamic model including tidal forces for studying hydrogen winds and corresponding atmospheric mass loss rates at HD209458b as a function of stellar XUV fluxes over evolutionary timescales. Depending on the assumed heating efficiency for hydrogen-rich Jovian-type thermospheres, the maximum temperature obtained in our study at 1.5 $R_{pl}$ by neglecting IR cooling reaches about 6000-10000 K. The corrsponding mass loss for present day conditions is ranging from 1-7 x $10^{10}$ g/s. By applying our model to higher XUV flux values as expected for young solar-like stars, we found that for a 100 times higher XUV exposure during the first 0.1 Gyr of the planets' evolution stage, loss rates up to 3.3 x $10^{12}$ g/s. The total integrated thermal mass loss over the history of HD209458b depends on the heating efficiency and XUV evolution of the planets' host star and is found to be in the order of about 8 x $10^{27}$-4.5 x $10^{28}$ g, corresponding to about 1-3.5 % of the mass of HD209458b.

***Acknowledgements.*** T. P. acknowledges support by the Marie Curie Fellowship Contract No. MTKD-CT-2004-002769 of the project “The influence of stellar high radiation on planetary atmospheres“, and the host institution INAF – Osservatorio Astronomico di Palermo. T. P., D. L., H. L., and H. K. B. acknowledge support by the Austrian Academy of Sciences, “Verwaltungsstelle für Auslandsbeziehungen” and by the Russian Academy of Sciences (RAS) for supporting working visits to the Institute of Computational Modelling (ICM/RAS) in Krasnoyarsk and at the Polar Geophysical Institute (PGI/RAS) in Murmansk, Russian Federation. This work is supported by the Austrian “Fonds zur Förderung der wissenschaftlichen Forschung” (FWF) under project P17099-N08, by grants 04-05-64088, 03-05-20014_BNTS_a from the Russian Foundation of Basic Research. Also acknowledged is support by the “Österreichischer Austauschdienst” (ÖAD), which supported this work by the project I.12/04 and I.2/04. Yu. N. K. and H. L. thank the Russian Foundation for the Basic Research, which partially supported this study as a joint Russian-Austrian project No. 03-05-20003 “Solar-planetary relations and space weather”. The authors also thank the Austrian Ministry for Science, Education and Culture (bm:bwk) and ASA for funding the CoRoT project.

This study was supported by the International Space Science Institute (ISSI) and carried out in the frame of the ISSI Team "Formation, Structure and Evolution of Giant Planets".

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