Energy-limited escape revisited: A transition from strong planetary winds to stable thermospheres

M. Salz\textsuperscript{1}, P. C. Schneider\textsuperscript{2,1}, S. Czesla\textsuperscript{1}, J. H. M. M. Schmitt\textsuperscript{1}

Talk given at OHP-2015 Colloquium

\textsuperscript{1}Hamburger Sternwarte, Universität Hamburg, Gojenbergs weg 112, 21029 Hamburg, Germany (msalz@hs.uni-hamburg.de)
\textsuperscript{2}European Space Research and Technology Centre (ESA/ESTEC), Keplerlaan 1, 2201 AZ Noordwijk, The Netherlands

Abstract

Hot Jupiters are thought to suffer from mass loss through planetary winds powered by strong high-energy irradiation. These photoevaporative winds can affect planetary evolution. We carried out photoionization-hydrodynamics simulations of the thermospheres of hot gas planets in the solar neighborhood using our new interface between the PLUTO and CLOUDY codes called TPCI. These detailed simulations reveal efficient radiative cooling in the atmospheres of massive and compact jovian planets, whose gravitational potential surpasses the critical limit of $\log_{10}(\Phi) > 13.11$ erg g$^{-1}$. In contrast to widely-made assumptions, our modeling shows that planets like HAT-P-2 b host stable thermospheres in radiative equilibrium, whereas smaller gas giants, indeed, show considerable mass-loss rates. Hence, the heating efficiency of the absorption of EUV radiation in the planetary thermospheres depends on the gravitational potential of the planet. We present a scaling law for the heating efficiencies that can be used in the well-known energy-limited escape formula and provides easily accessible mass-loss estimates for a wide range of irradiated planets from super-Earth type planets to the most massive hot Jupiters. The trend of the heating efficiency versus the gravitational potential is reflected in the planetary Ly$\alpha$ absorption and emission signals. These signals can be used to distinguish between two types of thermospheres in hot gas planets: strong, cool planetary winds with Ly$\alpha$ absorption and hot, stable thermospheres with Ly$\alpha$ emission.

1 Introduction

Planets on close orbits endure high irradiation levels. For example, CoRoT-2 b orbits an highly active host star at a distance of 0.028 au experiencing an high-energy irradiation level $10^5$ times stronger than that of Earth today (Schröter et al. 2011). This high-energy emission (X-rays and extreme ultraviolet radiation, XUV) is absorbed in upper atmospheric layers creating a so-called thermosphere. The absorption causes ionizations with subsequent thermalization of the photoelectron’s energy. The resulting energy input heats the planetary thermospheres to up to 20000 K, increasing their scale height so that the atmosphere can even expand beyond the planetary Roche lobe. The continuous radiative energy input must be balanced by an equally strong energy sink. In the thermosphere of Jupiter itself, thermal conduction stabilizes the energy input through high-energy irradiation (Yelle & Miller 2004), but this channel is not sufficient for hot gas planets (Yelle 2004).

If radiative cooling is small, the thermospheres of hot gas giants must expand to balance the radiative energy input. This expansion converts internal energy into gravitational potential energy by lifting material against the gravitational attraction of the planet. Thus, the high-energy irradiation creates a planetary wind that carries off material into interplanetary space, where it interacts with the stellar wind and radiation pressure (Tremblin & Chiang 2013; Bourrier & Lecavelier des Etangs 2013). If hot gas planets maintain strong magnetic fields, atmospheric escape can be inhibited in regions of closed field lines, which also affects the planetary mass-loss rates (Trammell et al. 2014; Khodachenko et al. 2015), but currently our knowledge about exoplanetary magnetic fields is limited (e.g. Bhrothia et al. 2014).
Expanded planetary atmospheres have been found in the five systems HD 209458 b, HD 189733 b, WASP-12 b, 55 Cancri b, and GJ 436 b mostly through excess absorption in atomic lines (Vidal-Madjar et al. 2003; Lecavelier des Etangs et al. 2010; Possati et al. 2010; Ehrenreich et al. 2012; Kulow et al. 2014). The spectrally resolved absorption signals often show strong blue shifts with velocity offset of up to ~250 km s$^{-1}$ (Lecavelier des Etangs et al. 2012), indicating that the detected material is indeed escaping from the planetary atmosphere. The presence of heavier atoms like carbon and oxygen in the upper atmospheres also requires the presence of strong winds to prohibit mass segregation and the development of a planetary homosphere (Vidal-Madjar et al. 2004; Linsky et al. 2010; Ben-Jaffel & Ballester 2013).

Models of the atmospheric escape are becoming more and more advanced, however, a complete picture of the complex environment is challenging. One class of simulations focuses on the interactions of the planetary wind with the stellar wind, radiation pressure, and the planetary magnetic field, however, without solving the energetics of the formation of the planetary wind (e.g., Bourrier & Lecavelier des Etangs 2013; Tremblin & Chiang 2013; Trammell et al. 2014; Krislyakova et al. 2014). Another class focuses on the formation of a planetary wind in the thermosphere without solving further interactions (Yelle 2005; Tian et al. 2005; García Muñoz 2007; Murray-Clay et al. 2009; Koskinen et al. 2013; Shakhovlamov et al. 2014). Combined models are now emerging (Khodachenko et al. 2015), indicating the true complexity of the system, however, at the moment these models do not include the full extent of the chemical network in the planetary atmospheres (e.g., compare García Muñoz 2007; Koskinen et al. 2013).

2 Energy-limited escape

Neglecting all complexities, energy conservation provides a quick estimate for the planetary mass-loss rates by setting the radiative energy input equal to the gravitational potential energy gained through lifting atmospheric material from the planetary surface to the Roche lobe height (Erkaev et al. 2007). Adopting reasonable heating efficiencies for the absorption of high-energy radiation in the planetary thermospheres, this energy-limited mass-loss rate can indeed be reached in planetary atmospheres (Watson et al. 1981; Murray-Clay et al. 2009). The energy-limited mass-loss rate $\dot{M}_d$ is given by (Erkaev et al. 2007; Sanz-Forcada et al. 2010):

$$\dot{M}_d = \frac{3\beta^2 \eta F_{XUV}}{4KG\rho_{pl}}.$$  

Here, $\beta$ is a correction for the size of the planetary atmosphere that absorbs XUV radiation, $\eta$ is the heating efficiency, $F_{XUV}$ is the combined X-ray plus extreme ultraviolet radiation flux at the planetary distance, $K$ is a correction for taking into account the limited size of the planetary Roche lobe (Erkaev et al. 2007), $G$ is the gravitational constant, and $\rho_{pl}$ is the mean planetary density.

3 Simulations

We have used a photoionization-hydrodynamics solver to simulate the escaping atmospheres of 18 hot gas planets in the solar neighborhood on a spherically symmetric 1D grid including hydrogen and helium in the planetary atmospheres (Salz et al. 2015b). The code (TPCI) is an interface between the MHD code PLUTO and the photoionization equilibrium solver CLOUDY (Mignone et al. 2007; 2012; Ferland et al. 1998; 2013; Salz et al. 2015a). We focus on the formation of a planetary wind by accurately solving the energy conversion throughout the planetary thermosphere. The use of the photoionization solver was crucial for our results, because CLOUDY self-consistently solves the absorption of XUV radiation and the emission of the planetary atmosphere. For example, the absorption of photoionizing radiation is solved by balancing the ionization ladder for each element, including photoionization with wavelength dependent cross-sections, induced recombination, recombination, collisional ionization, Auger electrons, and collisional ionizations through supra-thermal electrons.

TPCI further solves the emission of the planetary thermospheres, for example, line emission, free-free emission of electrons, and recombination cooling. The precise solution of the radiative heating and cooling rates throughout the planetary thermosphere allows us to compute the heating efficiency in individual planetary atmospheres. While TPCI can be used to simulation the escaping atmospheres, it can also solve hydrostatic thermospheres, where the radiative energy input is completely re-emitted. Thus, the code is well suited to study the conditions under which a planetary atmosphere becomes hydrodynamically stable.
4 The transition from strong winds to stable atmospheres

Figure 1 compares the thermospheres of HD 209458 b and HD 189733 b. While HD 189733 b experiences a 16 times higher irradiation level, the planet is heavier and more compact. According to Eq. 1, the energy limited mass-loss rate is 5 times higher than that of HD 209458 b (Salz et al. 2015b). However, our simulations show that HD 189733 b actually produces a weaker wind than HD 209458 b. Efficient radiative cooling brings the atmospheric layers below 1.5 \( R_{pl} \) close to radiative equilibrium, with only little energy remaining to accelerate the planetary wind (see Fig. 1(d)). The average heating efficiency of only \( 8.3 \times 10^{-3} \) is reduced by Ly\( \alpha \) and free-free emission in the 3000 K hotter thermosphere. Comparing all our simulations, we find that a planet with a deeper gravitational potential well \( \Phi_G = \frac{-GM}{R_{pl}} \) has a hotter thermosphere that cools more efficiently. Therefore, the planetary wind becomes weaker.

Indeed, the decrease of the heating efficiency in massive planets can hardly be avoided. To overcome the higher gravitational attraction a massive planets requires a higher thermospheric temperature, but the strong increase of radiative cooling with temperature hinders the thermosphere to heat up sufficiently. Therefore, the atmospheric scale height is smaller in massive planets, resulting in a reduced thermospheric density. This lower density reflects the weaker planetary wind, because the velocity of an isolated planetary wind is always slightly supersonic, which is close to 10 km s\(^{-1}\) in all planetary thermospheres.

5 Evaporation efficiencies

For each simulated planetary wind, we computed the individual evaporation efficiency given by the fraction of the simulated mass-loss rate to the energy-limited value (Salz et al. 2015c). In contrast to the heating efficiency, the evaporation efficiency includes the conversion of radiative energy into kinetic and thermal energy (Lopez et al. 2012). The values are plotted versus the planetary gravitational potential in Fig. 2. We find that for planets with \( \log_{10} (-\Phi_G) > 13.11 \) erg g\(^{-1}\) the evaporation efficiency declines rapidly and when the logarithm of the gravitational...
potential exceeds a value of 13.6 in units of erg g\(^{-1}\). At this point the planetary atmospheres become collisionless before any significant acceleration of a planetary wind occurs. Such thermospheres are hydrodynamically stable and re-emit nearly the complete XUV radiative energy input through Ly\(\alpha\) and free-free emission.

![Figure 2: Dependency of the evaporation efficiency on the planetary gravitational potential](image)

We fitted a broken power law to the simulation results (see Fig. 2). The fit provides evaporation efficiencies for any planet with a hydrogen dominated atmosphere based on its gravitational potential. These efficiencies can be used in the energy-limited mass-loss equation to provide quick mass-loss estimates based on the results of our detailed simulations. While the scatter of the values around the fit results from further influences on the simulated mass-loss rates, the values for the evaporation efficiency drop by several orders of magnitude depending only on the gravitational potential. These results can also be combined with the recombination limited mass-loss rates of Murray-Clay et al. (2009).

### 6 Planetary Ly\(\alpha\) absorption and emission signals

Four of the five detected expanded planetary atmospheres have been detected through Ly\(\alpha\) absorption during the planetary transit. A planetary wind transports large amounts of neutral hydrogen into the upper atmosphere and beyond the planetary Roche lobe (unbound hydrogen), and the more neutral hydrogen is present, the more absorption can be expected. Further interactions with radiation pressure or with the stellar wind can result in large radial velocity shifts but do not create additional neutral hydrogen. We compute the equivalent width of the Ly\(\alpha\) absorption signals from our simulations (following Cauley et al. 2015). This is a measure for the total strength of the planetary absorption signal. We do not compute spectrally resolved signals, because of the approximation of spherical symmetry and the omission of further interactions in the simulations.

Figure 3 shows that the clear trend of the evaporation efficiencies versus the planetary gravitational potential is reflected in the Ly\(\alpha\) absorption signals. Massive planets with hot and almost stable atmospheres produce very little Ly\(\alpha\) absorption. Smaller planets with strong, cool, and highly neutral winds can produce very large absorption signals.

These results reflect the trend seen in observations. GJ 436 b was detected with the largest Ly\(\alpha\) absorption signal (Kulow et al. 2014; Ehrenreich et al. 2015) and in our simulations this planet hosts one of the strongest and most neutral winds, causing strong Ly\(\alpha\) absorption. HD 209458 b also produces a strong signal, while in HD 189733 b the wind is weaker and more highly ionized causing less absorption. Again this corresponds with the observations, where in HD 209458 b strong Ly\(\alpha\) absorption was detected repeatedly (Vidal-Madjar et al. 2003, 2004; Ehrenreich et al. 2008), but in HD 189733 b the absorption is time-variable and possibly occurs only when the planetary wind is enhanced by strong stellar activity (Lecavelier des Etangs et al. 2012 and Wheatley 2015, see this conference proceedings). The simulation results also agree with the non-detection of Ly\(\alpha\) absorption during the transit of the super-Earth 55 Cnc e (Ehrenreich et al. 2012). This planet can produce a strong hydrogen dominated wind, but the...
extreme irradiation level quickly ionizes hydrogen limiting the extend of the neutral hydrogen cloud to values that are challenging for a detection.

Figure 3: Planetary Ly\textalpha absorption and emission signals plotted versus the planetary gravitational potential \cite{Salz2015}. Green dots give the equivalent width of the absorption signal and blue crosses indicate the maximal planet-to-star Ly\textalpha flux ratio. Small planets cause strong absorption but little emission and massive planets cause little absorption but strong emission.

While the hot and almost stable atmospheres of massive planets produce little absorption, they efficiently convert stellar XUV emission into Ly\textalpha radiation. This strongly enhances the contrast of the planetary Ly\textalpha emission compared to the stellar flux. \cite{Menager2013} found that the Ly\textalpha emission of HD 189733 b could be detectable during the orbital phases 0.25 and 0.75, when the planetary emission has a radial velocity offset from the stellar emission by the orbital velocity. We follow these authors and compute the maximal planet-to-star Ly\textalpha flux ration during these phases in all our simulations by assuming that only the illuminated half the planetary surface is emitting \cite{Salz2015}. Figure 3 shows that the trend of the decreasing evaporation efficiency is reflected by an increasing Ly\textalpha brightness of massive planets. Small planets with cool and strong winds do not strongly emit or reflect Ly\textalpha emission, but massive planet are Ly\textalpha bright and reach flux ratios of several percent compared to their host star. Such high flux ratios are possibly detectable with the Hubble Space Telescope today.

7 Conclusions

The evaporation efficiencies in the thermospheres of hot gas planets differ by several orders of magnitude depending on the gravitational potential of the planet. Smaller planets like GJ 436 b efficiently use the XUV irradiation to power a planetary wind. For such planets we find an average evaporation efficiency of \( \eta_{\text{eva}} = 0.23 \). In contrast, the XUV irradiation is almost completely re-emitted in massive planets like HAT-P-2 b via Ly\textalpha and free-free emission, leading to hot and stable thermospheres.

Planetary Ly\textalpha absorption and emission signals can be used to distinguish between the two types of thermospheres in hot gas planets. Smaller planets produce powerful, cool, and neutral planetary winds that cause large Ly\textalpha absorption signals. Massive hot Jupiters host hot, highly ionized, and almost stable thermospheres that cause little Ly\textalpha absorption but are strong Ly\textalpha emitters. A detection of planetary Ly\textalpha emission can be seen as clear indication of a stable thermosphere, because only the conversion of XUV irradiation into Ly\textalpha emission results in high planet-to-star Ly\textalpha flux ratios.

Acknowledgments: Thank you to the organizers of this great conference.
References


Koskinen, T. T., Harris, M. J., Yelle, R. V., & Lavvas, P. 2013, Icarus, 226, 1678


