Evaporation of hot jupiters and hot neptunes

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Abstract. Among the nearly five hundred extra-solar planets known, almost 30% orbit closer than 0.1 AU from their parent star. We will review the observations and the corresponding models of the evaporation of these 'hot jupiters'. The observations started with the discovery made with *HST* that the planet orbiting HD 209458 has an extended atmosphere of escaping hydrogen. Subsequent observations obtained with *HST*/STIS and *HST*/ACS confirm the escape of the gas. Even more, oxygen and carbon have been shown to be present at very high altitude in the upper atmosphere. Observations of other targets like HD 189733 and WASP-12 show that evaporation is a general phenomenon which could contribute to the evolution of planets orbiting close to their parent stars. To interpret these observations, we developed models to quantify the escape rate from the measured occultation depths. Numerous models have also been published to investigate mechanisms which can lead to the estimated escape rate. In general, the high temperature of the upper atmosphere heated by the far and extreme UV combined with the tidal forces allow a very efficient evaporation of the upper atmosphere. We will review the different models and their implications.

1. Introduction

Planetary transits are golden opportunities to probe the atmospheres of extrasolar planets. The atmospheric signals obtained with this method are usually tenuous, and few of them are firmly established. One of the strongest case is the detection in the visible of neutral atomic sodium in the hot jupiter HD 209458b. The sodium signature, a mere $\sim 2 \times 10^{-4}$ absorption, was obtained both from medium- to high-resolution, space-born and ground-based spectrographs (Charbonneau et al. 2002; Snellen et al. 2008) and secured by several independent data analyses (e.g., Sing et al. 2008a,b). In the ultraviolet (UV), planetary transits of HD 209458b have produced several remarkably large spectroscopic signatures, which are seen as absorptions in the emission lines originating from the stellar chromosphere (see Ehrenreich 2010 for a review). These large UV signatures, compared to the visible transit of the whole planet (1.6%; Charbonneau et al. 2000; Henry et al. 2000), require the presence of an extended and evaporating H I upper atmosphere, or exosphere, to the planet. Similar UV observations have been recently carried out on different planets to find out whether atmospheric evaporation is a property common among hot jupiters. In this paper, I review the new results obtained on exoplanets HD 189733b and WASP-12b, as well as new high-resolution observations of the exospheric signature of HD 209458b. Then, I describe what sort of signature could

be expected for planets less massive than hot jupiters, such as the neptunian planet GJ 436b.

2.   Observations of the exospheres of extrasolar planets

2.1   Lyman-α transits of hot jupiters

The strongest atmospheric signature observed for an exoplanet was obtained during the transit of the prototypical hot jupiter HD 209458b. It is a $(15 \pm 4)\%$ absorption in the stellar Lyman-α (Lyα) emission line of neutral atomic hydrogen (H I). This result was obtained with medium-resolution spectra taken with the Space Telescope Imaging Spectrograph (STIS) on the *Hubble Space Telescope* (*HST*) (Vidal-Madjar et al. 2003). It was later confirmed from new observations at lower resolution from STIS (Vidal-Madjar et al. 2004) and the Advanced Camera for Surveys (ACS) on *HST* (Ehrenreich et al. 2008). It was also strengthened by independent data analysis (Ben-Jaffel 2007, 2008; see Vidal-Madjar et al. 2008). The large absorption requires the presence of an extended H I upper atmosphere, or exosphere, to the planet. This envelope is necessarily evaporating because (i) it must fill the planetary Roche lobe to account for the size of the absorptions, and (ii) the H I atoms must be accelerated by the stellar radiation pressure beyond the escape velocity of the planet to account for the absorption in the wings of the Lyα line (Vidal-Madjar et al. 2003). New cases of atmospheric escape have been recently reported for two hot jupiters. Lecavelier des Etangs et al. (2010) use *HST*/ACS to detect the H I exosphere of HD 189733b at Lyα. Figure 1 compiles all Lyα transit light curves obtained so far, for HD 209458b and HD 189733b. Finally, Fossati et al. (2010) present observations of the highly irradiated planet host star WASP-12 with the Cosmic Origins Spectrograph (COS) on board *HST*, and interpret the tentative detection of extra absorptions in the metal lines of the star during the transit as signs of mass loss. Thus, atmospheric evaporation could be a common phenonemon among close-in planets.

Modelling Lyα transit light curve, as done in Fig. 1 allows the mass loss rate ($\dot{m}$) and the stellar high-energy flux ($F_{\mathrm{X/EUV}}$) to be constrained. In the case of HD 189733b, Lecavelier des Etangs et al. (2010; see their Fig. 13) find $10^{10} \lesssim \dot{m} \lesssim 10^{11}$ g s^{-1} and $F_{\mathrm{X/EUV}} \sim 20\times$ the solar value. The mass loss rate is negligible regarding the total mass of the planet, yet it has a dramatic impact on the observable size of the planet's upper atmosphere, for increasing values of $\dot{m}$.

2.2   Heavy elements in the exosphere of HD 209458b

The presence of elements heavier than hydrogen (C and O) at high altitudes has been surmised from unresolved *HST*/STIS observations (Vidal-Madjar et al. 2004). Their presence requires an hydrodynamic escape (or blow-off) of the upper atmosphere, with the flow of escaping H I carrying heavier species up to the Roche limit (Vidal-Madjar et al. 2004; Linsky et al. 2010), where they are swept away by radiation pressure (Lecavelier des Etangs et al. 2004). The tentative detections presented in Vidal-Madjar et al. (2004) were retrieved in an independent analysis of the same data set (Ben-Jaffel & Sona Hosseini 2010). The detection of C II was recently confirmed at a higher signal-to-noise level by new observations of the Cosmic Origins Spectrograph (COS) on *HST* (Linsky et al. 2010), shown in Fig. 2. These authors additionally report an absorption in the emission line of ionized silicon (Si III) that had not been seen previously. Assuming hydrodynamic model values for the gas temperature, outflow velocity at the limb of the outflow as seen in the C II lines, and solar abundances, Linsky et al. (2010) find

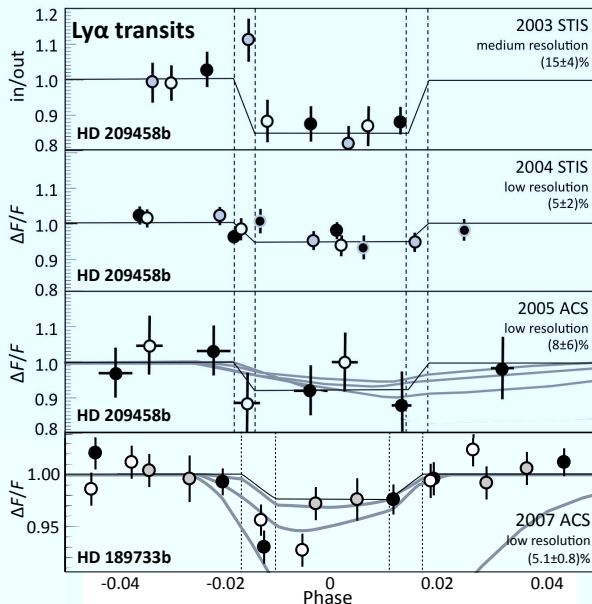mass-loss rates in the range $(8\text{–}40) \times 10^{10}$ g s^{-1}.

Figure 1: *Lyman-α transit light curves obtained for HD 209458b ((a)Vidal-Madjar et al. 2003, (b) Vidal-Madjar et al. 2004, and (c) Ehrenreich et al. 2008) at different resolutions and HD 189733b ((d) Lecavelier des Etangs et al. 2010). Different colors indicate different transits. Gray curves are model light curves produced by particle simulations of the atmospheric escape.*

The more significant observing results are summarized in Table 1 for each species and planet. These results have initiated a comprehensive modeling effort from different groups (e.g., Lecavelier des Etangs et al. 2004; Lecavelier des Etangs 2007; Lecavelier des Etangs, Vidal-Madjar, & Désert 2008; Yelle 2004, 2006; Tian et al. 2005; García-Muñoz 2007; Schneiter et al. 2007; Hubbard et al. 2007; Penz et al. 2008; Davis & Wheatley 2009; Murray-Clay, Chiang & Murray 2009). The global picture given by the above-cited models suggests that the upper atmospheres of close-in giant planets must be heated by the stellar X-rays, extreme and far UV, to about 10 000 K.[1] The canonical atmospheric mass loss rate $\dot{m}$ derived by these models is between 10^{10} and 10^{11} g s^{-1}. In this case, evaporation should not severely impact the life of observed giant planets. Meanwhile, it could be more critical for lower-mass planets such as hot neptunes.

3. Evaporation of hot neptunes

I use the case of GJ 436b, the first transiting neptune-mass exoplanet, to illustrate how we can predict the observable depth of the UV transit, i.e., the size of the signature

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[1]A similar temperature has been actually measured in the thermosphere of HD 209458b (Ballester, Sing, & Herbert 2007)
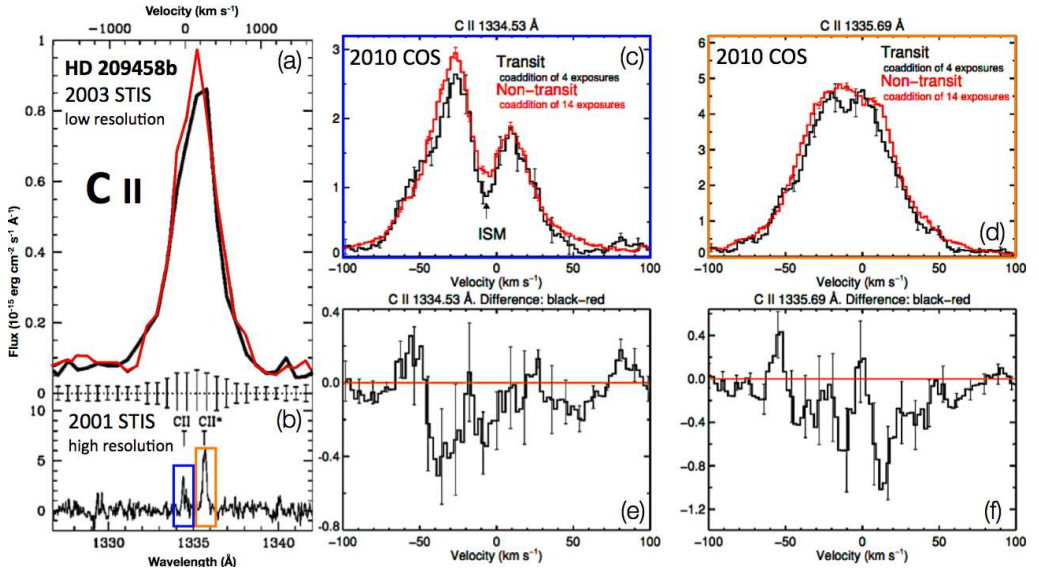
Figure 2: *In-transit absorptions in the C II doublet. (a) Low-resolution data of the with the in-transit (black) and out-of-transit (red) stellar emission (Vidal-Madjar et al. 2004). (b) High-resolution STIS spectrum. (c,d) High-resolution COS spectra of both components of the C II doublet. (e,f) Subtractions of the black and red curves from panel (c) and (d), showing the velocity structure in the exospheric absorptions*

of the planet's upper atmosphere in transmission spectroscopy. Various models (e.g., Figueira et al. 2009) predict an hydrogen envelope for this planet, based on its location in a mass-radius diagram. GJ 436b lies significantly above the mass-radius relation for a planet composed by 100% water (Gillon et al. 2007; see their Fig. 3). Ultraviolet transmission spectroscopy could be used to detect the hydrogen envelope.

Table 1: *Exoplanet atmospheric detections from UV transits*

Species	Resolved?	$\Delta F/F$ (%)	transit detection	atmosphere detection	Refs.
HD 209458b					
H I	Yes	$15 \pm 4\%$	3.8σ	3.4σ	(1)
O I	No	12.8 ± 4.5	2.8σ	2.5σ	(2)
C II	Yes	7.8 ± 1.3	6σ	4.8σ	(3)
Si III	Yes	8.2 ± 1.4	5.9σ	4.7σ	(3)
HD 189733b					
H I	No	5.1 ± 0.8	6.4σ	3.4σ	(4)
WASP-12b					
Mg II	No	3.0 ± 0.5	6σ	2.5σ	(5)

References. (1) Vidal-Madjar et al. 2003; (2) Vidal-Madjar et al. 2004; (3) Linsky et al. 2010; (4) Lecavelier des Etangs et al. (2010); (5) Fossati et al. (2010).
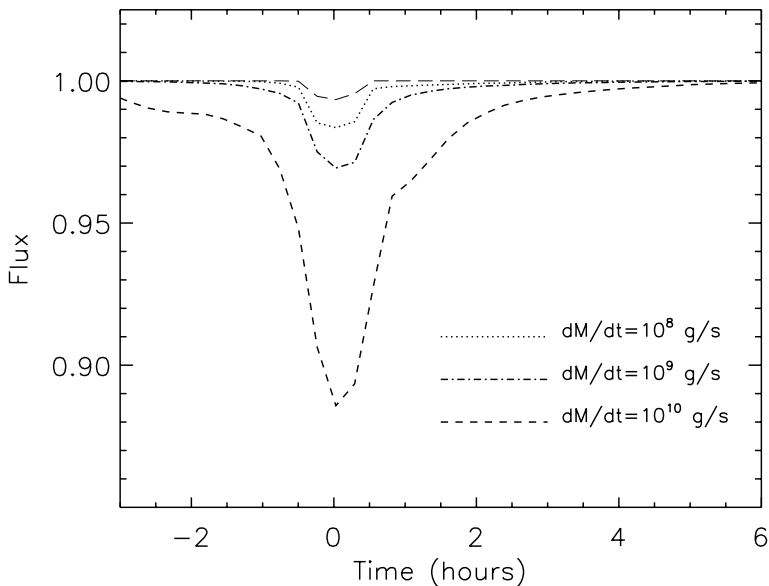
Figure 3: *Predicted Lyα transit light curves for the hot neptune GJ 436b, assuming different possible values of the mass loss rate. From Ehrenreich, Lecavelier des Etangs & Delfosse (submitted).*

The framework is that of an energy-limited atmospheric escape, where the mass loss rate is approximately proportional to the amount of energy radiated from the star at short wavelengths (X/EUV). In fact, this radiated energy is used to overcome the potential gravitational energy of the planet (which includes the tidal forces resulting from the proximity of the star), following $-\mathrm{dE}'_{\mathrm{pot}} = \eta \mathrm{dE}_{\mathrm{X/EUV}}$. The η factor accounts for the heating efficiency of the planet's thermosphere by high-energetic radiation. So far, this factor is still unconstrained for extrasolar planets. Following Lecavelier des Etangs (2007), it is possible to calculate for each transiting planet – and for a given value of η – an atmospheric mass loss rate $\dot{m}$. For GJ 436b, $\dot{m}$ is estimated between 10^8 and 10^{10} g s^{-1} for η between 0.01 and 1, respectively (Ehrenreich & Désert, submitted).

To calculate a theoretical set of H I transit light curves for this range of mass-loss rates, one needs to know the Lyα brightness of the star. Ehrenreich, Lecavelier des Etangs, & Delfosse (submitted) present a *HST*/STIS spectrum of the M dwarf GJ 436 at Lyα. From this observation, they derive a Lyα flux of $\sim 2 \times 10^{-13}$ erg s^{-1} cm^{-2}. They use this information to predict Lyα transit light curves for different $\dot{m}$, as shown in Fig. 3. The depth of the obtained Lyα light curve ($\sim 11\%$ for $\dot{m} \sim 10^{10}$ g s^{-1}) will allow the hydrogen envelope to be detected with *HST*. This prediction also opens new perspectives for the atmospheric characterization of other hot neptunes and even for the atmospheric detection of hot super-earths.

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