

LETTER TO THE EDITOR

# Temporal variations in the evaporating atmosphere of the exoplanet HD 189733b

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## ABSTRACT

Atmospheric escape has been detected from the exoplanet HD 209458b through transit observations of the hydrogen Lyman- $\alpha$  line. Here we present spectrally resolved Lyman- $\alpha$  transit observations of the exoplanet HD 189733b at two different epochs. These HST/STIS observations show, for the first time, that there are significant temporal variations in the physical conditions of an evaporating planetary atmosphere. While atmospheric hydrogen is not detected in the first epoch observations, it is observed at the second epoch, producing a transit absorption depth of  $14.4 \pm 3.6\%$  between velocities of  $-230$  to  $-140$  km s<sup>-1</sup>. Contrary to HD 209458b, these large velocities cannot arise from radiation pressure alone and require an additional acceleration mechanism, such as interactions with stellar wind protons. The observed absorption can be explained by an atmospheric escape rate of neutral hydrogen atoms of about  $10^9$  g s<sup>-1</sup>, a stellar wind velocity of  $190$  km s<sup>-1</sup> and temperature of  $\sim 10^5$  K.

An X-ray flare from the active star seen with Swift/XRT 8 hours before the second epoch observation supports the idea that the observed changes within the upper atmosphere of the planet can be caused by variations in the stellar wind properties, or by variations in the stellar energy input to the planetary escaping gas (or a mix of the two effects). These observations provide the first indication of interaction between the exoplanet's atmosphere and stellar variations.

**Key words.** Stars: planetary systems - Stars: individual: HD 189733

## 1. Introduction

Observations of the transiting extrasolar planet HD 209458b in the Lyman- $\alpha$  line of atomic hydrogen (H I) have revealed that this planet is losing gas (Vidal-Madjar et al. 2003). Subsequent theoretical studies indicate that atmospheric escape (so called 'evaporation') arises from the intense stellar X-ray and extreme ultraviolet energy input into the upper atmosphere (Lammer et al. 2003; Lecavelier des Etangs et al. 2004; Yelle 2004), leading to moderate escape rates for massive hot-Jupiters, or to formation of planetary remnants when strong evaporation implies a dramatic change in the planet mass (Lecavelier des Etangs et al. 2004, 2007; Charpinet et al. 2011).

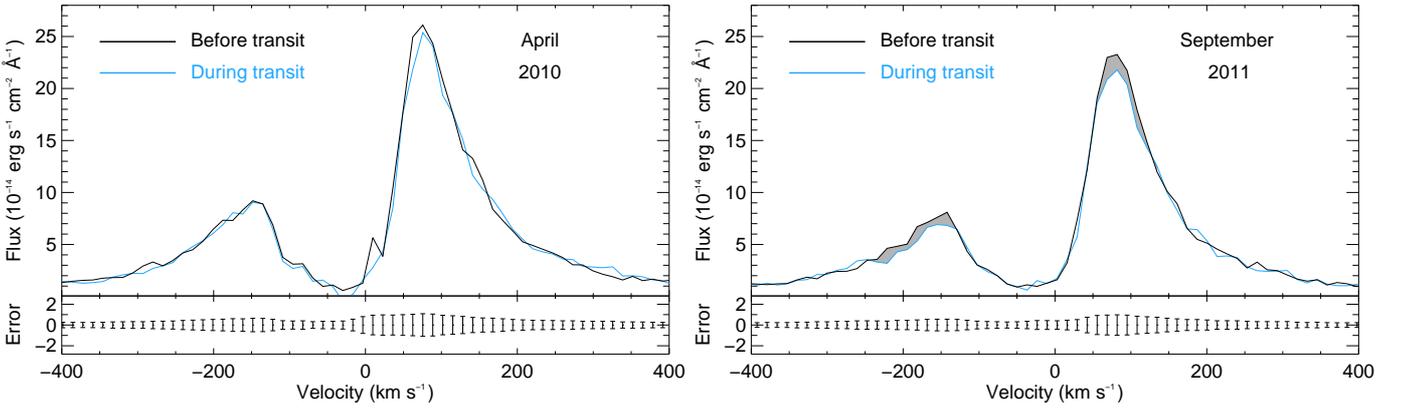
Despite the importance of evaporation on the fate of planets at short orbital distances, the physics of the exospheric gas and role of the star-planet system properties remain debated (García Muñoz 2007; Schneider et al. 2007; Holmström et al. 2008; Lecavelier des Etangs et al. 2008; Murray-Clay et al. 2009; Ben-Jaffel & Sona Hosseini 2010; Guo 2011). This is further compounded by the limited number of observations (Vidal-Madjar et al. 2004; Ballester et al. 2007; Ehrenreich et al. 2008; Fossati et al. 2010; Linsky et al. 2010), which include non-spectrally resolved Lyman- $\alpha$  observations of the exoplanet HD 189733b (Lecavelier des Etangs et al. 2010).

## 2. Observations, data analysis and results

### 2.1. Observations

To address these issues, we observed two transits of HD 189733b on 6 April 2010 and 7 September 2011 with the Space Telescope Imaging Spectrograph (STIS) onboard the Hubble Space Telescope (HST). The data consist of time-tagged observations obtained with the G140M grating, producing time-resolved spectra from 1195 to 1248 Å with a spectral resolution of about  $20$  km s<sup>-1</sup> at 1215.6 Å (Lyman- $\alpha$ ) with exposure times of 1800 to 2100 seconds. Between each consecutive HST orbit, data acquisition is interrupted for about 3500 seconds by the Earth's occultation. The obtained spectra show stellar emission lines of H I Lyman- $\alpha$ , Si III (1206.5 Å), O V (1218.3 Å) and the N V doublet (1242.8 Å and 1238.8 Å).

For both the 2010 and 2011 observations, data were recorded during two HST orbits before the transit, one orbit during the transit, and one orbit after the transit. We measured the transit signature of the planetary atmosphere by comparing spectra taken during transit to those taken before and after the transit event. For each stellar line, we calculated transit light curves of the total emission flux and of the flux within given wavelength ranges; the signature of the planetary atmosphere is detected as an excess absorption during the planet's transit. Because no at-



**Fig. 1.** The Lyman- $\alpha$  emission line of HD 189733 in April 2010 and September 2011. Spectra obtained before (black) and during the transits (blue) are displayed as a function of radial velocity relative to the star. The double-peaked profile results from a single stellar emission line absorbed at the centre by interstellar hydrogen which produces a broad absorption feature from about  $-100$  to  $+50$   $\text{km s}^{-1}$ . While no transit signatures are detected in 2010, two absorption regions are detected at more than  $3\text{-}\sigma$  during the transit of 2011; these regions are plotted by grey zones. They are seen at the top of the red wing around  $+80$   $\text{km s}^{-1}$  and, most significantly, in the blue wing with a  $\sim 100$   $\text{km s}^{-1}$  wide absorption around  $-200$   $\text{km s}^{-1}$ .

ospheric signature is detected in Si III, O V or N V lines, hereafter we consider only the Lyman- $\alpha$  observations.

The Lyman- $\alpha$  line is the brightest stellar line in our STIS spectra from 1195 to 1248  $\text{\AA}$ , and has a total flux of about  $1.8 \times 10^{-13}$   $\text{erg s}^{-1} \text{cm}^{-2}$  (about 10 times brighter than for HD 209458). With the resulting high signal-to-noise ratio, there is no need to co-add several observations to detect signature of the atmosphere, as needed for the STIS observations of HD 209458b and for the observations of HD 189733b with the Advanced Camera for Surveys (ACS) of the HST (Vidal-Madjar et al. 2003; Lecavelier des Etangs et al. 2010). This allows for the first time a search for temporal variations in the physical conditions of the planetary upper atmosphere between two observational epochs (here 17 months apart), as done for the deeper atmosphere using emission spectroscopy (Grillmair et al. 2008).

## 2.2. Detection of temporal variations in the evaporating atmosphere

The Lyman- $\alpha$  emission line from HD 189733 is spectrally resolved. At the resolution of the G140M grating, the line is composed of two peaks separated by a deep absorption due to interstellar atomic hydrogen (Fig. 1). In the raw data, the stellar emission line is superimposed with the geo-coronal airglow emission from the upper atmosphere of the Earth (Vidal-Madjar et al. 2003). This geo-coronal emission can be well estimated and removed in the final spectrum using the CALSTIS data pipeline (version 2.32 of 5 November 2010). Independent re-analysis of raw data using the same methodology as for STIS observations of HD 209458 (Désert et al. 2004) confirms that the airglow does not affect our measurements. Moreover, having used a narrow spectrograph slit of  $0.1''$ , the airglow contamination is limited to the central part of the Lyman- $\alpha$  line and does not contaminate the line wings where the transit atmospheric signatures are detected (see below). The data of September 2011 exhibits a notably low airglow emission level.

The Lyman- $\alpha$  observations of April 2010 do not show an atmospheric transit signature. In these data, the transit depth for the total flux of the whole Lyman- $\alpha$  line is  $2.9 \pm 1.4\%$ , in agreement with the  $2.4\%$  transit depth of the planet body alone as seen from visible to near infrared (Désert et al. 2009, 2011; Sing et al. 2011). In addition, we do not see any excess absorption in any portion of the Lyman- $\alpha$  spectral line profile.

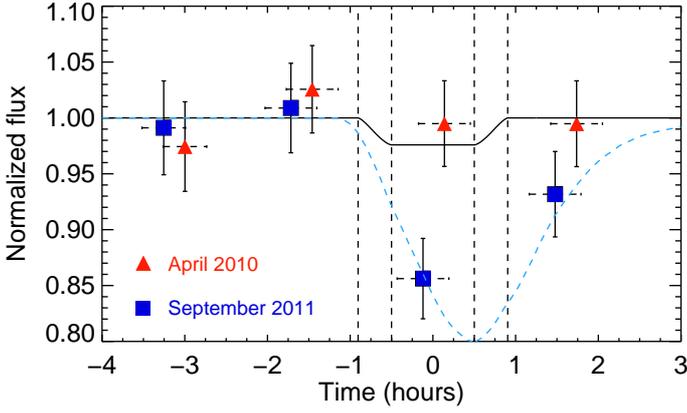
However, this situation strongly contrasts with the observations of September 2011, in which we see an excess absorption in the total flux of the Lyman- $\alpha$  line yielding a transit depth of  $5.0 \pm 1.3\%$ . This level is consistent with the results obtained with the non-resolved HST/ACS spectra of 2007-2008 (Lecavelier des Etangs et al. 2010). Importantly, the line profile shows two deep absorption regions at specific wavelength intervals during the transit: first in the blue part of the spectrum from about  $-230$   $\text{km s}^{-1}$  to  $-140$   $\text{km s}^{-1}$ , and in the red part of the spectrum from  $60$  to  $110$   $\text{km s}^{-1}$ .

In the blue wing of the Lyman- $\alpha$  spectrum of 2011, the most significant absorption shows up in the range of  $-230$  to  $-140$   $\text{km s}^{-1}$ , which gives an absorption depth of  $14.4 \pm 3.6\%$  ( $4\text{-}\sigma$  detection) corresponding to an excess absorption due to hydrogen atoms of  $12.3 \pm 3.6\%$ . The false positive probability to find such an excess anywhere in the whole searched range of  $-350$  to  $-50$   $\text{km s}^{-1}$  is only 7%. In the red wing of the Lyman- $\alpha$  spectrum of 2011, absorption is found in the range between  $60$  to  $110$   $\text{km s}^{-1}$ , producing an absorption depth of  $7.7 \pm 2.7\%$  ( $3\text{-}\sigma$  detection) and corresponding to an excess absorption due to hydrogen atoms of  $5.5 \pm 2.7\%$ . The false positive probability to find such an excess over the whole searched range [ $40$  to  $200$   $\text{km s}^{-1}$ ] is 39%. This high probability shows that the absorption seen in the red wing of the spectrum may not be real and is possibly due to statistical noise in the data, although interestingly enough, a similar absorption was also observed in the case of HD 209458b (Vidal-Madjar et al. 2003).

None of the excess absorption features detected in the September 2011 data are seen in the April 2010 data. We conclude that there are significant temporal variations of the physical conditions within the extended exosphere of this extrasolar planet between these two epochs (Fig. 2).

## 2.3. Models

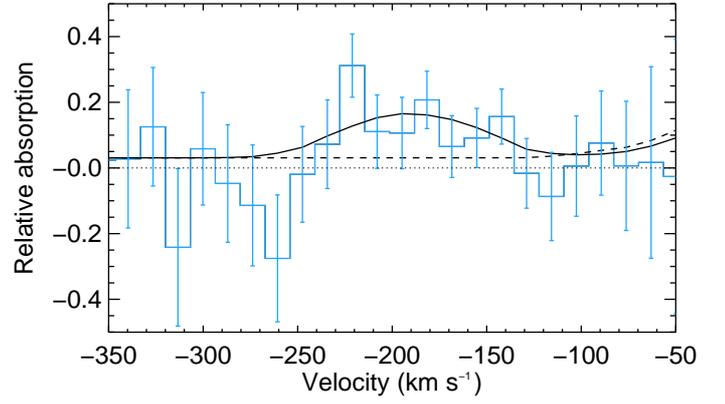
In September 2011, the absorption depth and velocity range show that neutral hydrogen atoms are present up to very high altitudes at velocities exceeding the escape velocity of  $60$   $\text{km s}^{-1}$ ; this unambiguously demonstrates that atmospheric gas must be escaping from HD 189733b. In the case of HD 209458b, the Lyman- $\alpha$  excess absorption was observed in the spectral range between  $-130$  to  $-50$   $\text{km s}^{-1}$ , which is well explained by the stellar radiation pressure accelerating hydrogen atoms up to



**Fig. 2.** Plot of the flux between  $-230$  and  $-140$   $\text{km s}^{-1}$  in the blue wing of the Lyman- $\alpha$  line, as a function of time relative to the center of the planetary transit. Vertical dashed lines show the beginning and end of ingress and egress of the transit. The red triangular symbols are for 2010 observations, while the blue square symbols correspond to observations of 2011. Horizontal error bars centered on the symbols show the duration of the exposures in each HST orbit. The time-tagged data allow independent sub-exposures to be extracted within each HST orbit (not shown here) resulting in the same transit signal within error bars. The light curve of the planet’s transit at optical wavelengths is displayed as a solid black line. The blue dashed line shows the calculated flux using the numerical simulation with an EUV ionizing flux 5 times the solar value, a stellar wind of protons with a temperature  $T \sim 10^5$  K, a velocity  $v \sim 190$   $\text{km s}^{-1}$  and density  $n \sim 3 \times 10^3$   $\text{cm}^{-3}$  together with an atmospheric escape rate of  $10^9$   $\text{g s}^{-1}$ .

$-130$   $\text{km s}^{-1}$  (Lecavelier des Etangs et al. 2008). The case here of HD 189733b showing excess absorption at higher velocities between  $-230$  and  $-140$   $\text{km s}^{-1}$  is more challenging to explain. Assuming a distance of 19.3 pc and following the method described in Ehrenreich et al. (2011), we estimate the interstellar medium absorption in the line wing and calculate the Lyman- $\alpha$  emission line profile as seen by the planet. From the extinction corrected line profile we estimate that radiation pressure can accelerate hydrogen atoms up to a radial velocity of  $-120$   $\text{km s}^{-1}$  in the exosphere of this planet (below this radial velocity the stellar flux at the corresponding wavelength in the core of the emission line is high enough for the radiation pressure to exceed the stellar gravity). Therefore, an additional acceleration mechanism beyond radiation pressure is required to explain the high radial velocities of hydrogen measured during the transit. Charge exchange with stellar wind protons can produce the observed large velocities (Holström et al. 2008; Ekenbäck et al. 2010).

To investigate this possibility and interpret the observed H $\alpha$  light curve, we developed a numerical Monte-Carlo simulation of the hydrogen atom dynamics. The details of the model will be given in a forthcoming paper (Bourrier et al. in preparation). In this N-body simulation, hydrogen atoms are released from HD 189733b’s upper atmosphere and rapidly accelerated by the radiation pressure up to  $120$   $\text{km s}^{-1}$  and then to higher velocities by charge exchange with protons from the stellar wind. This dynamical model provides the time-dependent distribution of positions and velocities of the escaping hydrogen atoms in the cloud surrounding HD 189733b. With this information, we calculated the corresponding absorption over the stellar emission line and the resulting transit light curve, which can be directly compared with the observations. We find that the observations are well fit with an escape rate of neutral hydrogen of about  $10^9$   $\text{g s}^{-1}$  and a stellar wind which has a temperature  $T \sim 10^5$  K, a density  $n \sim 3 \times 10^3$   $\text{cm}^{-3}$ , and a velocity  $\sim 190$   $\text{km s}^{-1}$ . The best-fit model



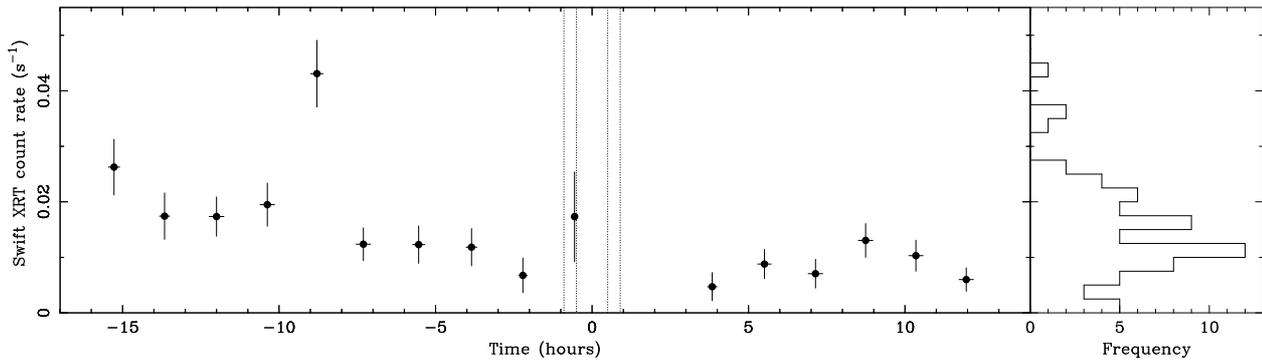
**Fig. 3.** Plot of the relative absorption observed in the blue wing of the Lyman- $\alpha$  stellar line (blue histogram) for the transit of September 7, 2011. The dashed line shows the model with radiation pressure only; in this case, there is no absorption at radial velocities below  $\sim -120$   $\text{km s}^{-1}$ , resulting in a large  $\chi^2$  of 22.8. If a stellar wind and charge exchange is considered, hydrogen atoms can be accelerated to the higher observed velocities. The model with an escape rate of  $10^9$   $\text{g s}^{-1}$  (solid line) gives a  $\chi^2$  of 13.0 for 17 degrees of freedom.

yields a  $\chi^2$  of 13.0 for 17 degrees of freedom for the absorption spectrum given in Fig. 3. The EUV flux controlling the neutral hydrogen ionizing timescale should be around 5 times the solar value to explain the moderate absorption observed after the transit of the planet (Fig. 2).

### 3. Swift X-ray simultaneous observations

The evaporation of hot Jupiters is driven by the X-ray/EUV irradiation of the planet by its parent star. In order to quantify the level of X-ray irradiation at the time of our observations in September 2011, we obtained contemporaneous observations with the X-ray telescope (XRT) of the Swift spacecraft (Gehrels et al. 2004). Toward HD 189733, a source was detected with a mean count rate of  $0.0119 \pm 0.0007$   $\text{s}^{-1}$ , consistent with previous XMM-Newton observations (Pillitteri et al. 2010), we do not detect the M-star binary companion, HD 189733B, but we do find evidence for a very weak hard X-ray source located about  $13''$  south of HD 189733A.

The Swift XRT spectrum of HD 189733 can be fit with a multi-temperature optically-thin thermal plasma model (Mewe et al. 1985; Liedahl et al. 1995) that is typical of the coronal X-ray emission from active stars. Using a three-temperature fit (temperatures of 0.12, 0.46 and 4.5 keV) we find an average X-ray flux in the 0.3-3 keV band of  $3.6 \times 10^{13}$   $\text{erg s}^{-1} \text{cm}^{-2}$ , consistent with XMM-Newton observations of HD 189733 (Pillitteri et al. 2011). This flux corresponds to a planetary irradiation rate of  $1.2 \times 10^{24}$   $\text{erg s}^{-1}$ , which could drive a mass loss rate of up to  $1.0 \times 10^{11}$   $\text{g s}^{-1}$  (assuming 100% evaporation efficiency and taking evaporation enhancement by tidal forcing into account; Lecavelier des Etangs et al. 2007; Erkaev et al. 2009). Assuming a realistic emission measure distribution (Sanz-Forcada et al. 2011), we can estimate the total luminosity across the X-ray/EUV band at the time of our observation to be  $7.1 \times 10^{28}$   $\text{erg s}^{-1}$ , corresponding to an energy limited evaporation rate of  $4.4 \times 10^{11}$   $\text{g s}^{-1}$ . The X-ray irradiation is consistent with the estimated escape rate which would thus require around 1% efficiency in the conversion of input energy into mass-loss (Ehrenreich & Désert 2011). Nonetheless this is only a lower limit because the estimated escape rate of neutral hydrogen atoms of about  $10^9$   $\text{g s}^{-1}$  does not include the escape of



**Fig. 4.** The Swift XRT X-ray light curve of HD 189733 around the time of September 7, 2011 transit. The data have been binned into one point per snapshot visit, with typical exposure times of around 27 minutes. Vertical dashed lines show the beginning and end of ingress and egress of the transit. A bright flare occurred about 8 hours before the transit. The observed average count rate during the flare snapshot is a factor 3.6 higher than the mean for the whole light curve, indicating a peak X-ray flux (0.3-3 keV) that must be less than  $1.3 \times 10^{-12}$  erg s $^{-1}$  cm $^{-2}$ . For comparison, the right panel shows the distribution for 63 epochs of Swift measurements (including the 16 obtained in September 2011), covering a wide range of timescales. The flare occurring shortly before the transit is the highest X-ray flux of all 63 measurements.

ionized hydrogen at the exobase of the atmosphere, and is thus a lower limit for the net escape from HD189733b.

The Swift XRT light curve of HD 189733 (Fig. 4) shows that the star exhibits significant X-ray variability, and most notably, a bright flare which occurred about 8 hours before the planetary transit. This flare could explain the observed variations in the extended cloud of high velocity hydrogen atoms escaping the planet, as it could affect the properties of the stellar wind needed to accelerate the atoms to the observed radial velocities. Besides, it is clear that the enhanced X-ray/EUV irradiation associated with this flare must lead to a significantly enhanced escape rate. With our best model parameters, an enhanced escape rate leads to a larger exospheric hydrogen cloud and thus to a stronger absorption after about one hour; the absorption remains at high level during a typical ionization timescale, which is constrained from the post-transit Lyman- $\alpha$  observations to be about 5 hours. Therefore, an X-ray flare occurring 8 hours earlier is expected to lead to a stronger escape rate detectable in the Lyman- $\alpha$  line.

#### 4. Conclusion

Being related or not to the observed X-ray flare, temporal variations in the evaporating atmosphere of HD 189733b are clearly detected in Lyman- $\alpha$ . The variability of the cloud of neutral hydrogen around HD 189733b can explain the high dispersion of absorption depths measurements in spectrally non-resolved Lyman- $\alpha$  observations (Lecavelier des Etangs et al. 2010); combining this with the present high signal-to-noise ratio spectrally resolved observations, we conclude that escape signatures are detected in about half of the total five transits observed in Lyman- $\alpha$ . Further simultaneous X-ray and Lyman- $\alpha$  observations are needed to obtain a better picture of the complex relationship between the stellar energetic input to the planet and the atmosphere's response to it, and to constrain theoretical models of space weather event on hot-Jupiters (e.g. Cohen et al. 2011). The HD 189733 system appears to be the target of choice, but future observations should also enlarge the diversity of stellar and planetary system properties to better disentangle the effects of the stellar-planet interactions from the intrinsic variability in the observed atmospheres.

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