TEMPORAL VARIATIONS IN THE EVAPORATING ATMOSPHERE OF THE EXOPLANET HD 189733B

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Abstract. Transit observations of the hydrogen Lyman-α line allowed the detection of atmospheric escape from the exoplanet HD209458b (Vidal-Madjar et al. 2003). Using spectrally resolved Lyman-α transit observations of the exoplanet HD 189733b at two different epochs, Lecavelier des Etangs et al. (2012) detected for the first time temporal variations in the physical conditions of an evaporating planetary atmosphere. Here we summarized the results obtained with the HST/STIS observations as presented in June 2012 at the SF2A 2012 meeting. While atmospheric hydrogen cannot be detected in the STIS observations of April 2010, it is clearly detected in the September 2011 observations. The atomic hydrogen cloud surrounding the transiting planet produces a transit absorption depth of 14.4±3.6% between velocities of -230 to -140 km s^{-1}. These high velocities cannot arise from radiation pressure alone and, contrary to HD 209458b, this requires an additional acceleration mechanism, such as interactions with stellar wind protons. The spectral and temporal signature of the absorption is fitted by an atmospheric escape rate of neutral hydrogen atoms of about 10^9 g s^{-1}, a stellar wind with a velocity of 190 km s^{-1} and a temperature of $\sim 10^5$ K.

We also illustrate the power of multi-wavelengths approach with simultaneous observations in the X-rays obtained with Swift/XRT. We detected an X-ray flare about 8 hours before the transit of September 2011. This suggests that the observed changes within the upper part of the escaping atmosphere can be caused by variations in the stellar wind properties, or/and by variations in the stellar energy input to the planet's escaping gas. This multi-wavelengths approach allowed the simultaneous detection of temporal variations both in the stellar X-ray and in the planetary upper atmosphere, providing first observational constraints on the interaction between the exoplanet's atmosphere and the star.

Keywords: Stars: planetary systems , Stars: individual: HD 189733

1 Introduction

Discovery of hot-Jupiter atmospheric escape has been carried out using observations of the transiting extrasolar planet HD 209458b in the Lyman-α line of atomic hydrogen H I (Vidal-Madjar et al. 2003). The so-called 'evaporation' is caused by energy input from the star into the upper atmosphere in the extreme ultraviolet and X-rays (Lammer et al. 2003; Lecavelier des Etangs et al. 2004; Yelle 2004). Evaporation can lead to moderate escape rates for massive planets, or to formation of planetary remnants when intense evaporation implies a dramatic change in the planet mass (Lecavelier des Etangs et al. 2004, 2007; Charpinet et al. 2011).

The escape phenomenon is of prime importance on the fate of planets at short orbital distances. Nonetheless, the details of the physics of the exospheric gas remain debated (García Muñoz 2007; Schneiter 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). Moreover, we have only a limited number of observations in hand (Vidal-Madjar et al. 2004;

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Ballester et al. 2007; Ehrenreich et al. 2008; Fossati et al. 2010; Linsky et al. 2010; Lecavelier des Etangs et al. 2010). Note that, because HD189733b has been discovered in 2005 after the STIS breakdown, HD189733b could be observed before May 2009 in the UV only by using the ACS spectrograph which provides non-resolved Lyman-α observations. The non-resolved Lyman-α spectra gathered in 2007-2008 provided first indications of the atmospheric escape from HD 189733b (Lecavelier des Etangs et al. 2010).

2 Observations, data analysis, and results

2.1 Observations

Lecavelier des Etangs et al. (2012) observed with HST/STIS two transits of HD 189733b in April 2010 and September 2011. The data consist of time-resolved spectra from 1195 to 1248 Å with a spectral resolution of about $20\,\mathrm{km\,s^{-1}}$. They show stellar emission lines of H I Lyman-α, Si III (1206.5 Å), O V (1218.3 Å) and the N V doublet (1238.8 Å and 1242.8 Å). However the Si III, O V, and N V lines do not show any planetary atmosphere signatures, and here we will focus on the Lyman-α line and summarize the results obtained by Lecavelier des Etangs et al. (2012).

The Lyman-α line of HD189733b is very bright ($1.8\times10^{-13}\,\mathrm{erg\,s^{-1}\,cm^{-2}}$) and is about ten times brighter than that of HD 209458. In contrary to the STIS observations of HD209458b, there is no need to co-add several observations of HD189733b to detect the signature of the atmosphere. This provides the unprecedented opportunity to search for temporal variations in the planetary upper atmosphere.

2.2 Detection of temporal variations in the evaporating atmosphere

The resolved Lyman-α emission line from HD 189733 is composed of two peaks separated by the deep ISM absorption due to interstellar atomic hydrogen (Fig. 1). The stellar emission line is superimposed with the geo-coronal airglow from the Earth atmosphere (Vidal-Madjar et al. 2003). However, this has been shown to have a negligible effect, in particular for the September 2011 observations which benefit from a very low airglow emission level.

The Lyman-α observations of 2010 do not show any atmospheric transit signature. In 2010, the transit depth measured in the total flux of the Lyman-α line is 2.9±1.4%; this agrees with the 2.4% transit depth of the planet body alone as seen in the optical. Most importantly, there is no excess absorption during the 2010 transit in any portion of the Lyman-α spectral line profile.

This strongly contrasts with the September 2011 observations. In these observations, there is an excess absorption in the total flux of the Lyman-α line with a transit depth of 5.0±1.3%, in agreement with the results obtained with the non-resolved HST/ACS spectra of 2007-2008 (Lecavelier des Etangs et al. 2010). More importantly, deep absorptions are detected during the 2011 transit in specific wavelength domains: in the blue wing of the spectrum from $-230\,\mathrm{km\,s^{-1}}$ to $-140\,\mathrm{km\,s^{-1}}$, and in the red peak of the spectrum from 60 to $110\,\mathrm{km\,s^{-1}}$.

In the blue part of the Lyman-α spectrum of 2011, we measured an absorption depth of 14.4±3.6% (4-σ detection) from -230 to $-140\,\mathrm{km\,s^{-1}}$. This corresponds to an excess absorption of 12.3±3.6% (the 14.4% absorption is composed of 2.4% from the planetary disk, and 12.3% from atmospheric hydrogen). The false-positive probability to find this absorption during the transit anywhere in the blue wing of the spectrum is estimated to be only 3.6% (Bourrier et al., in preparation). The absorption found in the red wing of the 2011 spectrum ($7.7\pm2.7\%$ between 60 to $110\,\mathrm{km\,s^{-1}}$) has a false positive probability of 24.6% and is likely not a real signature. Nonetheless it is noteworthy that a similar absorption in the red peak of the line has also been observed in HD 209458b (Vidal-Madjar et al. 2003).

The most important result is the observation of significant temporal variations of the physical conditions within the extended exosphere of this extrasolar planet between 2010 and 2011, 17 months apart (Fig. 2).

2.3 Models

The neutral hydrogen atoms detected in September 2011 present a large absorption depth (corresponding to a large extension of the absorbing cloud at high altitude in the exosphere of the planet) and a velocity range exceeding the escape velocity ($v_{esc}\sim60\,\mathrm{km\,s^{-1}}$). This unambiguously demonstrates that atmospheric gas is escaping from HD 189733b.

In HD 209458b, the Lyman-α excess absorption was observed between -130 to -50 km s^{-1}. This can readily be explained by the stellar radiation pressure accelerating hydrogen atoms up to -130 km s^{-1} (Lecavelier des Etangs et al. 2008). The higher velocities (-230 to -140 km s^{-1}) observed in HD189733b are more challenging to explain. Following the procedure described in Ehrenreich et al. (2011), we calculated the Lyman-α emission line profile as seen from the planet. We estimated that the radiation pressure accelerate hydrogen atoms up to the radial velocity of -120 km s^{-1} (below this radial velocity the stellar flux in the core of the emission line is sufficiently high for the radiation pressure to exceed the stellar gravity). We conclude that an acceleration mechanism other than radiation pressure, like the charge exchange with stellar wind protons (Holström et al. 2008; Ekenbäck et al. 2010), is required to explain the hydrogen velocities observed in 2011.

We investigate the scenario of charge exchange to interpret the observed HI light curve, using a numerical Monte-Carlo N-body simulation of the hydrogen atoms dynamics. The details of the model will be given in a forthcoming paper (Bourrier et al. in preparation). In this simulation, hydrogen atoms are released from the planet upper atmosphere. Because of the radiation pressure from the (well-known) Lyman-α stellar emission, the atoms are rapidly accelerated up to 120 km s^{-1}, and then accelerated to higher velocities by charge exchange with stellar wind protons. This dynamical model allows us to reproduce the observed profile of the spectral absorption and the transit light curve (Fig. 3). The observations are well-fitted with an escape rate of neutral hydrogen of about 10^9 g s^{-1} and a stellar wind density $n \sim 3 \times 10^3$ cm^{-3}, temperature $T \sim 10^5$ K, and velocity ~ 190 km s^{-1}. We also concluded that the EUV ionizing flux should be about 5 times the solar value to explain the moderate absorption after the transit of the planet (Fig. 2, Bourrier et al. in preparation).

3   Swift X-ray simultaneous observations

The energy needed for the gas to escape the planet gravitational well is brought by the X-ray/EUV irradiation from the host star. While observing the transit of September 2011 with HST/STIS, we obtained simultaneous observations with the X-ray telescope (XRT) of Swift. The star HD189733 is detected in the X-ray with a count rate of 0.0119 ± 0.0007 s^{-1}. By fitting the Swift XRT spectrum of HD 189733, we found an X-ray flux of 3.6×10^{-13} erg s^{-1} cm^{-2} in the 0.3-3 keV band. Assuming 100% evaporation efficiency, this X-ray flux corresponds to a mass loss rate of 1.0×10^{11} g s^{-1} (a lower efficiency yields a proportionally lower escape rate; see details in Lecavelier des Etangs et al. 2012). Extrapolation of the high energy flux estimates to the X-ray/EUV band yields a corresponding energy-limited evaporation rate of 4.4×10^{11} g s^{-1}. Therefore, the observed X-ray irradiation is consistent with the escape rate estimated by Lecavelier des Etangs et al. (2012), which would thus require about 1% efficiency in the conversion of input energy into mass loss (Ehrenreich & Désert 2011). Note however that this is only a lower limit of the efficiency because the escape rate of neutral hydrogen atoms estimated using Lyman-α observations does not include the escape of ionized species and represent a lower limit for the net escape rate from HD189733b.

The Swift X-ray light curve shows that HD189733 exhibits significant X-ray variability (Fig. 4). Most notably, a bright flare occurred about 8 hours before the planetary transit of September 2011. This flare could explain the variations in the extended cloud of high-velocity hydrogen atoms escaping the planet. One possibility is a change of the properties of the stellar wind accelerating the atoms to the observed radial velocities, a change caused by or related to the observed X-ray flare. In another scenario, the enhanced X-ray/EUV irradiation caused by the X-ray flare can lead to a significantly enhanced escape rate which becomes detectable. A combination of these two scenarios is also possible.

4   Conclusions

Here we summarized the results obtained from HST/STIS and SWIFT/XRT simultaneous observations of HD189733b transit, as presented in Lecavelier des Etangs et al. (2012), which show the detection in Lyman-α of temporal variations in the evaporating atmosphere of HD 189733b. Further simultaneous X-ray and Lyman-α observations would be useful to improve the 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 a space weather event on hot-Jupiters (*e.g.* Cohen et al. 2011). The HD 189733 system appears to be the target of choice in the hot-Jupiter gallery, but future observations should also enlarge the diversity of planetary and stellar systems to better disentangle the effects of the planet-star interactions from the intrinsic (wheather-like) variability in the exoplanet atmospheres.
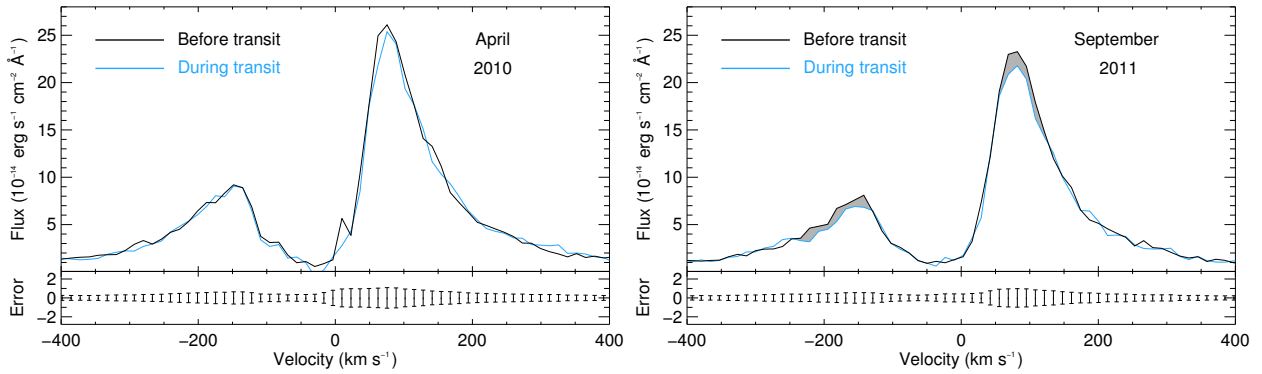
Fig. 1. Lyman-α emission line of HD 189733 measured before (black) and during the transits (blue), in 2010 and 2011. No transit signatures are detected in 2010. During the transit of September 2011 absorptions are detected at more than 3-σ at the top of the red wing and in the blue wing of the line.
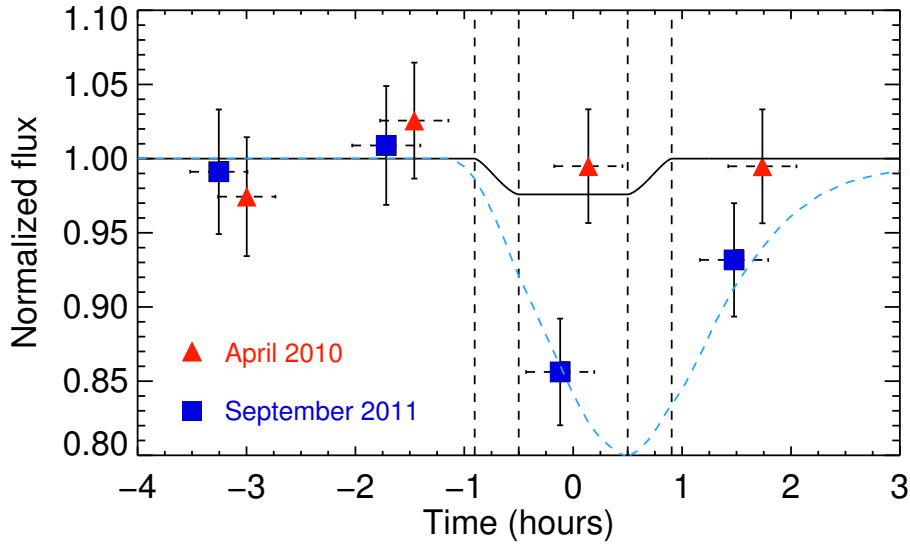

Fig. 2. Plot of the flux between -230 and -140 km s^{-1} in the blue wing of the Lyman-α line as a function of time. Dashed lines show the beginning and end (four contacts) of the transit. The red triangles are for the 2010 observations; the blue squares are for the 2011 observations. The solid black line shows the transit light curve at optical wavelengths. The blue dashed line shows the light curve calculated with the numerical simulations with an atmospheric escape rate of 10^9 g s^{-1}.

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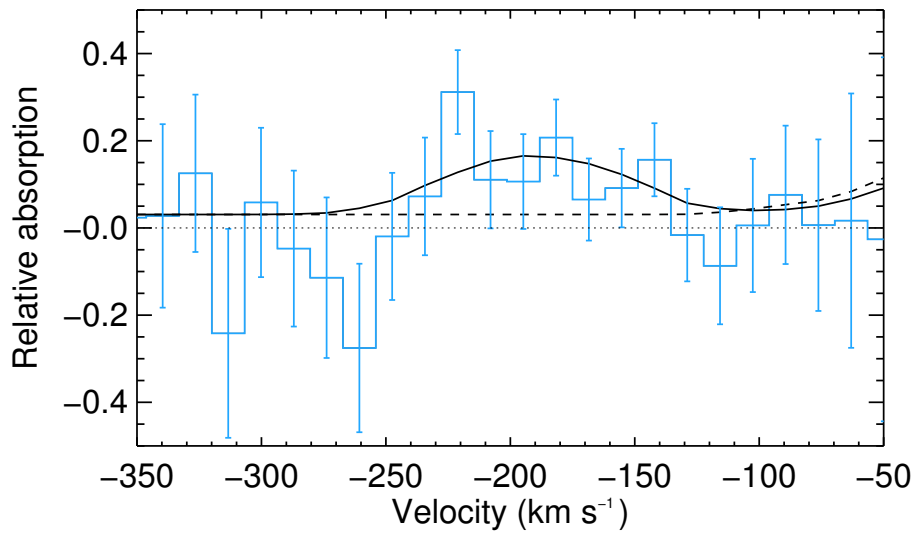Holmström, M., Ekenbäck, A., Selsis, F., et al. 2008, Nature, 451, 970

Fig. 3. Plot of the spectral profile of the transit HI absorption in the blue wing of the Lyman-α stellar line (blue histogram). The dashed line shows the model with radiation pressure only. If a stellar wind and charge exchange is considered, hydrogen atoms can be accelerated to the higher observed velocities. The model with radiation pressure, charge exchange with stellar wind protons, and an escape rate of $10^9 \, \mathrm{g \, s^{-1}}$ yields a good fit to the observation with a χ^2 of 13.0 for 17 degrees of freedom (solid line).
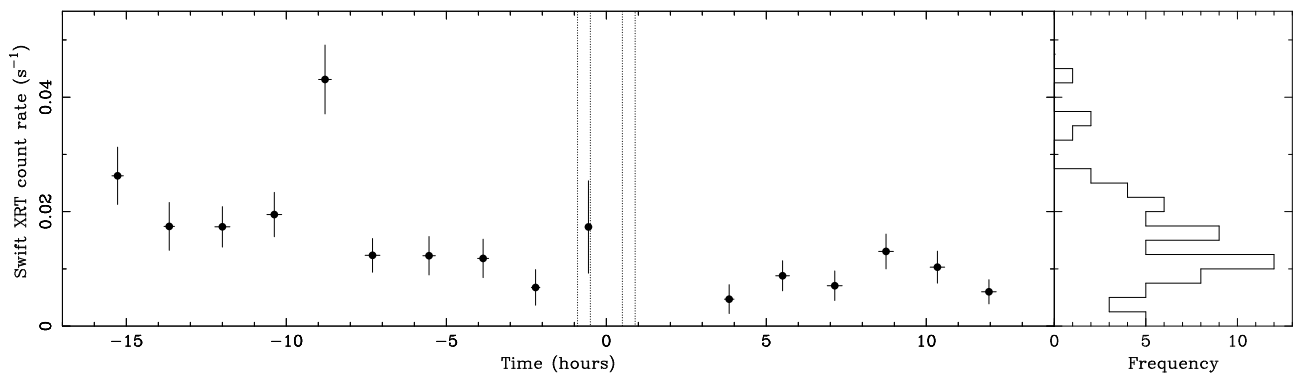

Fig. 4. Swift X-ray light curve of HD189733 in September 7, 2011. A bright X-ray flare occurred about 8 hours before the transit with an average count rate about a factor 3.6 higher than the mean value. The right panel shows the distribution for all available Swift measurements; the flare occurring before the transit is the highest X-ray flux in all of the 63 measurements.

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