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The hydrogen exosphere of exoplanet HD 209458b detected with *HST*/ACS

D. Ehrenreich[1], **A. Lecavelier des Etangs**[2], **G. Hébrard**[2],
J.-M. Désert[2], **A. Vidal-Madjar**[2], **J. C. McConnell**[3],
C. D. Parkinson[4], **G. E. Ballester**[5], **and R. Ferlet**[2]

[1]Laboratoire d'astrophysique de Grenoble, Université Joseph Fourier and CNRS (UMR 5571)
BP 53, 38041 Grenoble cedex 9, France
email: `david.ehrenreich@obs.ujf-grenoble.fr`

[2]Institut d'astrophysique de Paris, Université Pierre-et-Marie Curie and CNRS (UMR 7095)
98 bis, boulevard Arago 75014 Paris, France

[3]Department of Earth and Space Science and Engineering, York University
4700 Keele street, Toronto, Ontario M3J1P3, Canada

[4]Department of Atmospheric, Oceanic, and Space Sciences, University of Michigan
2455 Hayward street, Ann Arbor, Michigan 48109, USA

[5]Lunar and Planetary Laboratory, University of Arizona
1040 East 4th street, Tucson, Arizona 85721-0077, USA

Abstract. Exospheric atomic hydrogen escaping from the planet HD 209458b provides the largest observational signature ever detected for an extrasolar planet atmosphere. We present observations of this transiting planet's extended exosphere with the Advanced Camera for Surveys on board the *Hubble Space Telescope*. From the two transit light curves obtained at Lyman α, we find an in-transit absorption of $(8.0 \pm 5.7)\%$, in good agreement with previous studies. These new constraints on the size of the exosphere strengthens the evaporation scenario. Full details are provided in Ehrenreich *et al.* (2008).

1. Introduction

During a planetary transit, the stellar light is partially filtered by the planetary atmosphere before reaching the observer, who can thus probe the atmospheric limb structure and composition with a differential spectroscopic analysis. Numerous detailed models of extrasolar planet transmission spectroscopy have been developed (see, e.g., Brown 2001), and detections of atmospheric signatures have been particularly successful on the 'hot-Jupiter' HD 209458b using space- (e.g., the detection of H_2 on HD 209458b by Lecavelier des Etangs *et al.* 2008) and ground-based facilities (e.g., the re-detection of sodium by Snellen *et al.* 2008).

The dim absorption signatures (from $\sim 10^{-4}$ to 10^{-3}) obtained in the visible allow observers to probe for the lower atmosphere of the planet, throughout $\sim$1 000-km-thick layers. Compared to these rather tenuous signals, the $\sim 10\%$ absorption signatures of hydrogen (H I), carbon (C II), and oxygen (O I) detected by Vidal-Madjar *et al.* (2003, 2004) trace the extended upper atmosphere of the planet, the exosphere.

The proximity of HD 209458b to its star (0.045 AU) makes the gaseous planet receiving a colossal amount of extreme ultraviolet (EUV) irradiation. Such an energetic input heats the hydrogen upper atmosphere to $\sim 10^4$ K and inflates it to the Roche limit: the atmosphere is evaporating and its spatial extent produces the large absorption observed in the Lyman-α (Lyα) stellar emission line. The hydrogen mass-loss rate estimated from observations (Vidal-Madjar & Lecavelier des Etangs 2004) and theoretical modelling (e.g., Yelle 2004, 2006) are converging to $\dot{m}\!\sim 10^9$ to 10^{10} g s^{-1}. Unsolved questions are: is there a hydrogen comet-like tail trailing the planet? Does the size of this cloud depend on the stellar activity and variations in the flux of ionizing EUV radiation? What is the evaporation state of other close-in planets?

In fact, observational insights from other systems would significantly constrain and refine the modelling of the evaporation process in a more general frame. However, previous observations were accomplished with the Space Telescope Imaging Spectrograph (STIS) on board the *Hubble Space Telescope* (*HST*). The failure of STIS in August 2004 prevented the achievement of additional observations of exoplanets transiting bright stars like HD 209458, HD 189733, or HD 149026.

Observations of HD 209458 were instead performed with the Advanced Camera for Surveys (ACS; Ford *et al.* 2003) on board *HST*.

2. Observations and methods

The observations consist in 2 visits, performed with the ACS/Solar Blind Camera (SBC) and obtained on 2006 May 14 (visit 1) and 2006 May 31 (visit 2). Eight *HST* orbits in total were used for the following phase coverage of the transit light curve: 3 *HST* orbits were obtained before 1st contact, 4 orbits between 1st and 4th contacts, and 1 orbit after 4th contact. Each *HST* orbit consists in 8 exposures: a direct image of the star is first made with the F115LP filter; 6 exposures are then acquired in slitless spectroscopy mode with the PR110L prism; another direct image is finally taken with the F115LP filter. The data reduction summarized below (see Ehrenreich *et al.* 2008 for details) makes use of the standard calibrated products of the ACS pipeline.

The 2D spectral images are background-subtracted, corrected from geocoronal Lyα contamination, and co-aligned. We then perform on each image an aperture photometry over the unresolved stellar Lyα emission. The two time series subsequently obtained for visits 1 and 2 yield two transit light curves, which are normalized to correct for possible variations of the stellar Lyα flux between the 2 visits. The final light curve is plotted in the bottom panel of Fig. 1. It is fitted with a simple trapezoidal transit curve, where the geometry, i.e., the impact parameter and the transit, ingress, and outgress durations, are obtained from accurate photometry of the transit light curve in the optical (Knutson *et al.* 2007). The transit depth and the out-of-transit baseline level are free to vary to fit the data. Values for these free parameters are then obtained by minimizing a χ^2.

3. Results

We obtain a best-fit transit depth of $(8.0 \pm 5.7)\%$, with a $\chi^2/\nu = 67.6/40 \approx 1.7$. The quoted error bar was scaled up to take into account the actual dispersion of the points in our time series.

The observed difference between transit depths measured in the visible ($\sim 1.6\%$; Brown *et al.* 2001) and in the ultraviolet is indicative of an additional absorption centered around the Lyα emission line. The measured absorption is compatible with the $(5 \pm 2)\%$ measured by Vidal-Madjar *et al.* (2004) at an equivalent resolution with *HST*/STIS. The absorption of the stellar flux during the transit is approximately equal to the ratio of the planetary to stellar surfaces, $(R_p/R_\star)^2$. An absorption of $(8.0 \pm 5.7)\%$ thus corresponds to the *passage* of a spherical hydrogen cloud of radius $R_{\mathrm{H}} \approx (0.28 \pm 0.1)\ R_\star$, where $R_\star = 1.12\ \mathrm{R}_\odot$ is the stellar radius (Knutson *et al.* 2007). It gives $R_{\mathrm{H}} = (3.1 \pm 1.1)$ Jovian radii ($\mathrm{R_J}$), i.e., much larger than the planetary radius of $R_p = (1.32 \pm 0.02)\ \mathrm{R_J}$ measured in the optical by Knutson *et al.* (2007).

Because of the observed absorption over the unresolved Lyα line, the hydrogen upper atmosphere must either extend beyond the Roche lobe (if the absorption occurs within the narrow core of the Lyα line), or the atoms velocities must exceed the escape velocity (if the absorption occurs over the whole line or over a broad velocity range of about ± 200 km s^{-1}). Since the atmospheric escape takes place in both cases, the present result is a new independent confirmation of the presence of an extended hydrogen exosphere around HD 209458b, first observed and confirmed by Vidal-Madjar *et al.* (2003, 2004); it strengthens the atmospheric escape scenario.

The spectral resolution of data analyzed in the present study does not allow us to constrain the velocity of the observed hydrogen and to compare it to the escape velocity, as done by these last authors. A clear signature of hydrogen escaping from the planet gravity would be the observation of an escaping hydrogen 'cometary-like' tail trailing the planet orbit.

Vidal-Madjar & Lecavelier des Etangs (2004) used a particle simulation in which the escape rate $\dot{m}$ is a free parameter. Hydrogen atoms with velocities $\sim v_{\mathrm{esc}}$ are blown by the planet at $\dot{m}$ and sensitive to the known and wavelength-dependent stellar radiation pressure, that accelerates them to the high velocities observed. The radiation pressure on the moving planet carves the cloud of escaping atoms as a comet-like tail, trailing the planet. Schneiter *et al.* (2007) employed a three-dimensional hydrodynamical simulation to treat the interactions between the stellar wind blown at a fixed rate and an isotropic

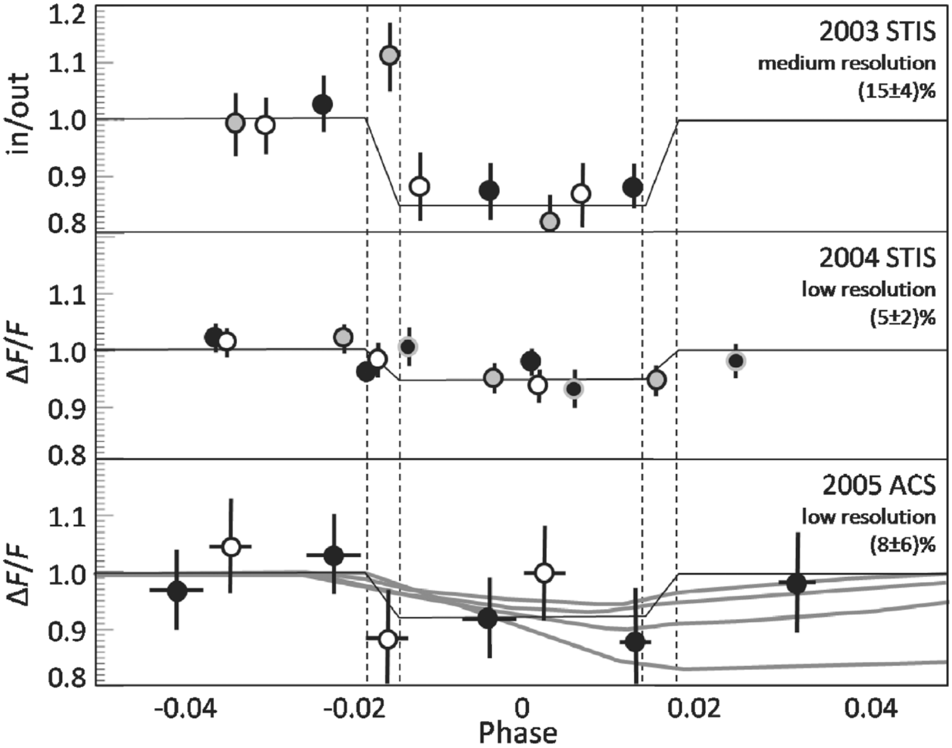

Figure 1. Ultraviolet transit light curves of HD 209458b at Lyα, for three different data sets. Different colours correspond to different *HST* visits. Trapezoidal fits to the light curves are included, whose depths have been determined by (from top to bottom) Vidal-Madjar *et al.* (2003, 2004) and the present study (see Ehrenreich *et al.* 2008). Theoretical light curves resulting from the passage of a hydrogen comet-like tail trailing the planet are figured in the bottom panel, for different mass-loss rates $\dot{m}$.

wind of H atoms ejected by the planet for various values of $\dot{m}$. Their simulations also show a cometary structure for the cloud of escaping material. Both simulations predict asymmetric transit light curves, which are reproduced in Fig. 1 over the observations, for different values of $\dot{m}$. These simulations fit our measurements correctly; however, the precision achieved in this data set does not allow us to put strong constraints on $\dot{m}$.

This study is indeed limited by the low accuracy of photometry constrained by photon noise. Higher resolution and more sensitive slit spectroscopy, associated with a better phase coverage of the transit aftermath, are needed to detect the hydrogen tail of the planet which is predicted by evaporation models.

While studies of the evaporation in other extrasolar planet, like HD 189733b, is still going on with the *HST*/ACS, high hopes are placed on the repair of STIS and the installation of the Cosmic Origin Spectrograph (COS) during *HST* Servicing Mission 4.

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