The long egress of GJ 436b’s giant exosphere

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ABSTRACT

The M dwarf GJ 436 hosts a transiting warm Neptune known to experience atmospheric escape. Previous observations revealed the presence of a giant hydrogen exosphere transiting the star for more than 5 h, and absorbing up to 56% of the flux in the blue wing of the stellar Lyman-α line of neutral hydrogen (H I Lyα). The unexpected size of this comet-like exosphere prevented observing the full transit of its tail. In this Letter, we present new Lyα observations of GJ 436 obtained with the Space Telescope Imaging Spectrograph (STIS) instrument onboard the Hubble Space Telescope. The stability of the Lyα line over six years allowed us to combine these new observations with archival data sets, substantially expanding the coverage of the exospheric transit. Hydrogen atoms in the tail of the exospheric cloud keep occulting the star for 10–25 h after the transit of the planet, remarkably confirming a previous prediction based on 3D numerical simulations with the EVaporating Exoplanet code (EVE). This result strengthens the interpretation that the exosphere of GJ 436b is shaped by both radiative braking and charge exchanges with the stellar wind. We further report flux decreases of 15 ± 2% and 47 ± 10% in the red wing of the Lyα line and in the line of ionised silicon (Si iii). Despite some temporal variability possibly linked with stellar activity, these two signals occur during the exospheric transit and could be of planetary origin. Follow-up observations will be required to assess the possibility that the redshifted Lyα and Si iii absorption signatures arise from interactions between the exospheric flow and the magnetic field of the star.

Key words. planetary systems - Stars: atmospheres, gaseous planets, individual: GJ 436

1 Introduction

Transit observations in the stellar Lyman-α line of neutral hydrogen (H I Lyα at 1 215.67 Å) allowed the detection of atmospheric escape from the two hot Jupiters HD 209458b (Vidal-Madjar et al. 2003, 2004) and HD 189733b (Lecavelier des Etangs et al. 2010, 2012; Bourrier et al. 2013), the warm giant 55 Cnc b (Ehrenreich et al. 2012), and the warm Neptune GJ 436b (Kuivalainen et al. 2014; Ehrenreich et al. 2015). The escaping hydrogen exospheres produce large Lyα absorption transit signatures ranging from 7.5 ± 1.8% for 55 Cnc b to 56.3 ± 3.5% for GJ 436b. Compared to close-in hot Jupiters, GJ 436b (25.4 ± 2.1 M⊕ and 4.10 ± 0.16 R⊕, Butler et al. 2004; Gillon et al. 2007; Lanotte et al. 2014) is gently irradiated by its M2v host star (Ehrenreich et al. 2011), yet it spots an extended hydrogen envelope, first hinted at by Kulow et al. (2014) and fully revealed by Ehrenreich et al. (2015). These authors found that GJ 436b emits a comet-like cloud of H atoms, with a coma bigger than the star and a tail extending millions of kilometers (up to 40% of GJ 436b’s orbit, 450 planetary radii), trailing the planet. Because of its unexpected, gigantic scale, past Lyα observations of GJ 436b’s exosphere could only cover the transit of its coma and the onset of its comet-like tail. Bourrier et al. (2015, 2016b) have modelled the dynamics of GJ 436b exospheric cloud using the EVaporating Exoplanet code (EVE; Bourrier & Lecavelier des Etangs 2013). Adjusting Lyα spectra obtained between 2010 and 2014, they show that the geometry and dynamical structure of the exospheric cloud could be explained by radiative braking (i.e. the effect on exosphere particles resulting from radiation pressure lower than stellar gravity; Bourrier et al. 2015) and stellar wind interaction (specifically, charge exchange; Bourrier et al. 2016b). The balance between both mechanisms, however, would shape the cloud tail, hence the egress of the UV transit, differently. Meanwhile, the full extent of the tail, provided by the egress duration, is unknown. Given the partial coverage (3–4 h) of the egress, new data were needed to fully cover the UV transit egress and precisely determine the nature of the star-planet interaction sculpting the cloud.

In this Letter, we present new Hubble Space Telescope (HST) data obtained with the Space Telescope Imaging Spectrograph (STIS). The combined reduction and analysis of these data covering a much larger fraction of the planetary orbit, with all previously existing data, is presented in Sect. 3 and Appendix B. Our results (Sect. 4) confirm the blueshifted Lyα absorption signature of Ehrenreich et al. (2015) and strengthen the interpretation of Bourrier et al. (2015, 2016b). We also find new surprising absorption signatures in the red wing of the H I Lyα line and in the ionised silicon line (Si iii) that could be of planetary or stellar origins.

2 Observations

In total, GJ 436b has been observed at eight epochs (hereafter Visits 0 to 7) with HST/STIS. All visits are listed in Table A.1. Visits 0 to 3 revealed the deep transit of GJ 436b’s exosphere in the blue wing of the Lyα line (Ehrenreich et al. 2011, 2015; Ku-
low et al. 2014). Three new visits (Visits 5 to 7) were obtained on 2016-Mar-30, 2016-Apr-06, and 2016-May-08 (General Observer (GO) programme 14222; PI: D. Ehrenreich) with the aim of completing the coverage of the exospheric transit, during the transit of the tail (−3 h; Visit 6), before the transit of the coma (≥−3 h; Visit 7), and after the presumed end of the transit (≥+20 h; Visit 5). Times are calculated using the ephemeris from Lanotte et al. (2014). All observations were made with the Far Ultraviolet Multi-Anode Microchannel Array detector (FUV-MAMA) detector and the G140M grating with a central wavelength of 1222 Å. The eight visits represent 27 HST orbits. Each orbit-long1 time-tag exposure has been divided into five sub-exposures (a reasonable balance between signal over noise ratio and time resolution) and processed through CALSTIS, the STIS pipeline, yielding a total of 135 spectra.

3. Analysis

3.1. Reference, unocculted Ly$\alpha$ flux

The new visits obtained before and after the exospheric transit allow us to reconstruct a reference spectrum seemingly unaffected by the exospheric absorption signature. We average the flux in the first HST orbits of Visits 0, 2, and 3 (as done by Ehrenreich et al. 2015) with the flux measured in all HST orbits obtained during Visits 4, 5, and 7. This average out-of-transit baseline spectrum appears stable in both the red wing of the Ly$\alpha$ line and the reference band (−250, −120] U [+120, +250] km s$^{-1}$), as can be seen in Fig. 1a,b. In the Ly$\alpha$ blue wing (Fig. 2), the flux of Visit 4 and the first exposure of Visit 5 are higher than in subsequent orbits used for the out-of-transit baseline. The origin of this wavelength-dependent rise is unclear, but in the following we chose to include them in the out-of-transit baseline flux. Excluding them will only decrease the out-of-transit baseline by less than 4%.

3.2. Correction of systematics

In addition to stellar variability, STIS G140M spectra are known to be impacted by an instrumental systematic effect caused by the telescope breathing. This effect is reported to be achromatic, thus to correct for it we need to locate a reference wavelength or velocity band in the Ly$\alpha$ emission feature devoid of astrophysical signal. The geocoronal emission line (airglow) contaminates the core of the observed stellar line, and varies in strength and position from one observation to another. This region is not adapted to our needs so we exclude it, setting conservative limits of [−40, +30] km s$^{-1}$ (velocities are expressed with respect to the Ly$\alpha$ line centre in the stellar rest frame). Previous work reported absorption signatures in the Ly$\alpha$ blue wing ([−120, −40] km s$^{-1}$; Ehrenreich et al. 2015) and, tentatively, in the Ly$\alpha$ red wing ([+30, +120] km s$^{-1}$; Kulow et al. 2014). These two bands, over which we will search for exospheric signatures, cannot be used to monitor telescope breathing. A careful inspection of the Ly$\alpha$ spectra presented in Fig. 3 allowed us to find two bands seemingly free of astrophysical signal, over [−250, −120] and [+120, +250] km s$^{-1}$, which we call the reference band. The flux integrated over these two bands, which can be seen in Fig. A.1c, remains about stable within the uncertainties for all visits, spanning over six years of observations. We hypothesized that all variations in these reference bands could be attributed to instrumental effect. Different strategies have been developed to correct for telescope breathing (see e.g. Bourrier et al. 2017, and references therein). In this work, we compare three correction methods: parametric (Bourrier & Lecavelier des Etangs 2013; Ehrenreich et al. 2012; Bourrier et al. 2016a), empirical (Deming et al. 2013; Wilkins et al. 2014; Berta et al. 2012; Ehrenreich et al. 2014), and non-parametric using Gaussian processes (GP; Appendix B). All three methods yield similar results. In the following, we opt to rely on the GP-based approach.

3.3. Flux in other spectral lines

Besides the prominent Ly$\alpha$ line, we detect the following stellar emission features in the STIS/G140M range (1 190–1 250 Å): Si$\text{iii}$ at 1 206.5 Å, N$\text{v}$ doublet at 1 238.8 and 1 242.8 Å, and O$\text{v}$ at 1 218.3 Å (cf. Table C.1). The low signal-to-noise ratio in these lines prevented us from doing an orbit-to-orbit comparison and establishing the stability of the stellar baseline flux for those lines. We therefore averaged their spectra within the orbital phase regions labelled A to E on Fig. 2 (cf. Table A.2): (A)

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1 The exposure time ranges from ~ 1 500 to 2 900 s.
before the exospheric transit signature in the blue wing of Ly\(\alpha\) (B) during the exospheric transit ingress, (C) during the optical transit (i.e. the transit of the planetary disk alone), (D) during the exospheric transit egress, and (E) after the exospheric transit. Regions (B), (C), and (D) are considered ‘in transit’; regions (A) and (E) are ‘out of transit’.

4. Results

4.1. Detection of the \(\text{Ly} \alpha\) transit egress

The most significant absorption signal is detected in the \(\text{Ly} \alpha\) blue wing between \(-120\) and \(-40\) km s\(^{-1}\) (Fig. 2), in agreement with Ehrenreich et al. (2015). Visit 6 (time from mid-transit \(\tau = [+4.01, +9.18]\) h) prolongates and confirms the exospheric egress suggested by Visits 1, 2, and 3. The egress duration is now constrained to be longer than \(-10\) h and shorter than \(-25\) h. The \(\text{Ly} \alpha\) flux measured during Visit 5 \((\tau = [+25.8, +31.0]\) h) is in good agreement with the Visit 0 measurement obtained \(-+30\) h after the mid-transit time, close to superior conjunction. We stress that those compatible measurements were obtained more than six years apart, highlighting the temporal stability of GJ 436. Bourrier et al. (2015, 2016a) fitted the spectra obtained during Visits 0 to 3 (all violet curves in Fig. A.2) with EVE. Their best-fit theoretical spectra yield the light curve plotted in Fig. 2. The model is in remarkable agreement with the new data from Visits 6 and 7, strengthening the interpretation proposed in Bourrier et al. (2015, 2016a): the weak UV radiation emitted by GJ 436 yields a low radiation pressure (\(-70\%\) of stellar gravity) and a low photoionisation of escaping hydrogen atoms. This, combined with a high planetary wind velocity (\(-55\) km s\(^{-1}\)), allows the planetary outflow to diffuse within a large coma surrounding and comoving with the planet, which further extends into a broad cometary tail (Bourrier et al. 2015).

In addition, escaping atoms interact with the slow stellar wind of the M dwarf (\(-85\) km s\(^{-1}\)) via charge exchanges abrading the day-side exosphere (Bourrier et al. 2016a). These interactions create a secondary tail of neutralised stellar wind protons\(^2\), which move with the persistent dynamics of the stellar wind and therefore yield different \(\text{Ly} \alpha\) absorption signatures over time than the primary tail. This model assumed that the out-of-transit baseline is provided by the flux measured during the ‘out-of-transit’ region defined in the previous section. Visits 4 and 7 tentatively suggest (Fig. 2), however, that the unocculted \(\text{Ly} \alpha\) line might be even brighter. This will have to be confirmed with additional measurements obtained between the superior conjunction and the first quadrature.

4.2. Detection of a redshifted \(\text{Ly} \alpha\) absorption signature

Visits 1 and 6 show similar integrated fluxes in the \(\text{Ly} \alpha\) red wing during and after the optical transit, with an average absorption depth of \(15 \pm 2\%\) compared to the baseline level (Figs. 1a & 3). In both visits, the absorption signature is located within \([+30, +110]\) km s\(^{-1}\) but at a different time from the mid-transit at \(+0.5\) and \(+6.6\) h, respectively. In comparison, the blueshifted absorption occurs around the mid-transit. This redshifted absorption is time variable. This was first noted by Kulow et al. (2014) from Visit 1 data; however, Ehrenreich et al. (2015) did not confirm it with same-phase data obtained during Visits 2 and 3. Visit 6 changes this picture and confirms the existence of a redshifted \(\text{Ly} \alpha\) signature delayed in time with respect to the blueshifted signature. Interpretation of this redshifted \(\text{Ly} \alpha\) signature is challenging: the EVE model that best fitted the blueshifted signature (Sect. 4.1) does predict the existence of H atoms moving towards the star, but redshifted by less than \(+50\) km s\(^{-1}\) because this population is localised within the coma and could not create a signature in the tail (see Fig. 4 in Bourrier et al. 2016a).

In the absence of radiation pressure or with a very strong self-shielding protecting the interior of the coma (which is not the case for GJ436b), Bourrier et al. (2015) showed that gravitational shear could lead to a stream of H atoms falling onto the star but ahead of the planet and thus yielding a redshifted signature before the optical transit (see their Fig. 2). Interestingly, tentative \(\text{Ly} \alpha\) redshifted absorptions have been previously reported in HD 209458b and HD 189733b (Vidal-Madjar et al. 2003; Lecavelier des Etangs et al. 2012) but in phase with the respective blueshifted absorptions signature of those planets.

It is plausible that stellar variability (Tian et al. 2009; Llama & Shkolnik 2016; Vidal-Madjar 1975) is the origin of the variations, because they are located at the peak of the observed red wing, which traces higher altitudes in the chromosphere of the star which are more active than the lower chromosphere which is the source for the far wings of the \(\text{Ly} \alpha\) line (e.g. Bourrier et al. 2017). However, the high stability of the stellar flux over six years of observations, the fact that the variations always correspond to a decrease of the flux with respect to the reference spectrum, and the fact that they appear to be phased during and after the planet transit, suggest another scenario.

Interaction of the exospheric flow with the star and planet magnetic fields could be one of the mechanisms that drives particles towards the star. A bow shock formed ahead of the planet by the interaction between the stellar wind and the planetary magnetosphere could only yield absorption before the planet transit (Alexander et al. 2016; Lai et al. 2010). Furthermore, Bourrier et al. (2016a) showed that the interactions between the exosphere and the stellar wind required to explain the absorption in the \(\text{Ly} \alpha\) blue wing imply that the planetary magnetosphere is embedded deep inside the coma. Strong magnetic connection could nonetheless link the embedded magnetosphere with the stellar magnetic field, forcing part of the planetary outflow to stream toward the star behind the planet (Strugarek 2016). One of the magnetised star-planet interactions proposed by Matsakos et al. (2015) (Type 4) bears some resemblance with our observations in the red wing, with planetary gas infalling nearly radially onto the star. The variability of the detected absorption could be explained by the continuous readjustment of the magnetic field topology as the planet orbits the star, with new magnetic accretion channels forming periodically. However, this scenario requires a high UV irradiation and a weak planetary outflow, which are not consistent with the mild irradiation from GJ 436 and the high velocities derived for the planetary outflow (Bourrier et al. 2016a). Furthermore, Matsakos et al. (2015) investigated the case of a hot Jupiter around a solar-type star, without accounting for radiation pressure despite its major role in shaping the exospheres of evaporating exoplanets. Gas in magnetised interaction regions is also expected to be strongly ionised, which would require either that massive amounts of neutral hydrogen infall toward the star or that shielding or recombination mechanisms allow for a significant portion of this gas to remain neutral.

4.3. Detection of an absorption signature from ionised silicon

The other stellar lines (Table C.1) are much fainter than \(\text{Ly} \alpha\), so we compared for each line the total fluxes averaged in transit

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\(^2\) These are stellar wind protons that gained an electron from the interaction with neutral hydrogen atoms in the exosphere.
Fig. 2. Light curves of GJ 436 integrated over the Lyα blue wing. Legend is the same as in Fig 1. The blue curve is the model calculated with EVE that represents the best fit to previous data (Visit 0 to 3).

(phase regions B, C and D) and out of transit (phase regions A and E). We report an absorption signal of 36 ± 15% in the O v line. The signal occurs during ingress and egress but not during the optical transit. Thus, it may not be of planetary origin. Loyd et al. (2017) observed GJ 436 with HST/Cosmic Origins Spectrograph (COS) from [−4, +3] h around the optical transit. Within this time range, they reported no detection of N v or Si iii absorption. This is in agreement with our analysis of the two N v lines. Meanwhile, we detect an absorption signal of 47 ± 10% in the Si iii line within [−50, +50] km s⁻¹, similar in intensity to the blueshifted Lyα absorption depth and occurring during the same phases as the exospheric transit. The flux is constant over the phase range covered by Loyd et al. (2017) (Fig. 1 c), suggesting that the stellar line was already absorbed during their observations, preventing them from detecting any variations. We note that our observations are compatible with their upper limit.

We cannot exclude stellar variations in the Si iii line (Loyd et al. 2017), which could be linked to the variation seen in the Lyα red wing (Sect. 4.2). A planetary origin for the Si iii signal is tantalising, as it would demonstrate the hydrodynamic nature of GJ 436b atmospheric escape, constrain the star-planet magnetic interaction, and provide a possible tracer for the presence of enstatite clouds (Mg₂Si₂O₆), potentially responsible for the flat near-infrared transmission spectrum of the lower atmosphere (Knutson et al. 2014). This will require additional observations.

5. Conclusion

We report new HST/STIS UV observations of the exospheric cloud escaping from the warm Neptune GJ 436b. A combined analysis of all available UV data, making use of GP to correct for systematics, yields the following results:

1. We detect the UV transit egress and constrain its duration between 10 to 25 h. This corresponds to a size of the exospheric hydrogen tail between 5 and 12 millions km. This result confirms previous observations (Ehrenreich et al. 2015) and their interpretation (Bourrier et al. 2015, 2016a).

2. We detect an absorption signal in the red wing of the Lyα line, which is delayed in time compared to the blueshifted absorption. This signal could originate either from the planet or be due to stellar activity.

3. We detect an absorption signal in the Si iii line, possibly linked with the Lyα redshifted signal (and stellar activity).

More observations will be needed at other phases to discriminate the stellar activity scenario from a planetary origin.

4. We notice the remarkable stability of GJ 436’s unocculted Lyα emission line over the six-year period (2010–2016) covered by the available observations.

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Appendix A: Log of observations and raw light curves

All spectra were linearly interpolated on a common wavelength grid, chosen to be the grid of Visit 0 first sub-exposure.
Table A.1. Observation log. Symbols in the first column refer to plotting symbols in Fig. A.1.

| Visit | Date       | Programme | PI      | HST orbits | Time from mid-transit (h) | Phase range  |
|-------|------------|-----------|---------|------------|---------------------------|--------------|
| 0 (⊙) | 01 May 2010| GO#11817  | Ehrenreich | 1          | [29.64, 30.03]            | [0.46, 0.47] |
| 1 (★) | 07 Dec 2012| GTO#12034 | Green    | 4          | [−2.03, 3.04]             | [−0.03, 0.05]|
| 2 (△) | 18 Jun 2013| GO#12965  | Ehrenreich| 4          | [−3.26, 1.75]             | [−0.05, 0.03]|
| 3 (△) | 23 Jun 2014| GO#12965  | Ehrenreich| 4          | [−3.30, 1.78]             | [−0.05, 0.03]|
| 4 (♂) | 25 Jun 2015| GO#13650  | France   | 2          | [35.29, 37.49]            | [−0.44, −0.41]|
| 5 (⊙) | 30 Mar 2016| GO#14222  | Ehrenreich| 4          | [25.86, 31.04]            | [0.40, 0.49] |
| 6 (♀) | 06 Apr 2016| GO#14222  | Ehrenreich| 4          | [4.01, 9.18]              | [0.06, 0.14] |
| 7 (♂) | 08 May 2016| GO#14222  | Ehrenreich| 4          | [−8.45, −3.28]            | [−0.13, −0.05]|
Table A.2. Orbital phases range

| Phase       | HST orbits                  |
|-------------|-----------------------------|
| range       | [visit #, (orbit #)]        |
| Before transit | [2,(1)], [3,(1)], [7,(1,2,3,4)] |
| Ingress     | [1,(1)], [2,(2)], [3,(2)]   |
| Optical transit | [1,(2)], [2,(3)], [3,(3)]  |
| Egress      | [1,(3,4)], [2,(4)], [3,(3)], [6,(1,2,3,4)] |
| After transit | [0,(1)], [4,(1,2)], [5,(1,2,3,4)]  |
Appendix B: Correction of systematics: Gaussian processes

This method differs from the parametric approach in that the shape of the function used to describe the systematics can be adjusted to capture any behaviour not encompassed by an analytical function. Gaussian processes (GP) are one of these methods. GP are widely use in machine learning and are increasingly popular in the exoplanet community (see Williams (2006) for a global introduction and Gibson et al. (2012) for an application in the exoplanet field). Within a GP scheme, the joint probability distribution for the reference band is a multivariate gaussian distributed about a mean function, a flat line representing a stable flux in our case. Systematics and white noise are characterised by the covariance matrix, which is defined by a covariance function (or kernel). In this analysis we adopt the squared exponential kernel in addition to a white kernel: \( k(t, t') = \exp(-\frac{(t-t')^2}{2l^2}) + \delta_{tt'}\sigma^2 \).

The hyperparameter \( l \) of the squared exponential kernel defines a characteristic length scale above which data points are not correlated. The white noise is incorporated through a variance term \( \sigma^2 \) (an hyperparameter) with \( \delta_{tt'} \) being the Kronecker function. The white noise should describe the pipeline error bars and the length scale should be of the order of one HST visit duration. Having a shorter length scale can allow us to reproduce shorter features providing a better correction of the systematics. However, it may lead to an over fitting. GP are implemented using George (Ambikasaran et al. 2014).

We note that Visit 0 only has one orbit, which makes the correction of the breathing effect ambiguous as its reproducibility between orbits of the same visit cannot be assessed. Therefore, we did not correct the fluxes from this visit.
Apart from the Lα line, we have identified several other lines: Si iii at 1206.51 Å, N v at 1238.821, 1242.804 Å, and O v at 1218.344 Å. Those lines have a flux two magnitudes lower than the Lα line. The flux measured during one single orbit is in a photon-starved regime and can present strong variations of magnitude (even a negative flux) and shape from one orbit to another. We therefore averaged all the spectra within the orbital phase regions labelled A to E on Fig. 1 (cf. Table A.2): (A) before the exospheric transit signature in the blue wing of Lyα, (B) during the exospheric transit ingress, (C) during the optical transit, (D) during the exospheric transit egress, and (E) after the exospheric transit. Regions (B), (C), and (D) are considered ‘in-transit’; regions (A) and (E) are ‘out of transit’. We consider the flux integrated in the velocity band [-50,50] km s\(^{-1}\). Let \(F_{\text{in}}\) and \(F_{\text{out}}\) be those fluxes during the transit and out of the transit respectively (dashed lines in Fig C.2). The absorption is defined as \(1 - F_{\text{in}}/F_{\text{out}}\). Table C.1.1 shows results for each line. The N v lines are summed together in the velocity space. No absorption is observed for this specie. An absorption signal is measured in the O v line, but it may not be related to the planet as only the ingress and egress fluxes are absorbed. Finally, an absorption signal in Si iii line correlated with the planet transit is detected at almost five sigma (see Sect. 4.3).

**Appendix C: Other lines**

Apart from the Lα line, we have identified several other lines:

| Species | Wavelength [Å] | Stellar flux \((10^{-16} \text{erg cm}^{-2} \text{s}^{-1})\) | Absorption [%] |
|---------|---------------|---------------------------------|---------------|
| Si iii  | 1206.510      | 3.8 ± 0.3                       | 47 ± 10       |
| O v     | 1218.344      | 2.2 ± 0.2                       | 36 ± 15       |
| N v     | 1238.8        | 5.5 ± 0.3                       | -0.07 ± 12    |