Lyα in the GJ 1132 System: Stellar Emission and Planetary Atmospheric Evolution

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Abstract

GJ 1132b, which orbits an M dwarf, is one of the few known Earth-sized planets, and at 12 pc away it is one of the closest known transiting planets. Receiving roughly 19× Earth’s insolation, this planet is too hot to be habitable but can inform us about the volatile content of rocky planet atmospheres around cool stars. Using Hubble Space Telescope Imaging Spectrograph spectra, we search for a transit in the Lyα line of neutral hydrogen (Lyα). If we were to observe a deep Lyα absorption signature, that would indicate the presence of a neutral hydrogen envelope flowing from GJ 1132b. On the other hand, ruling out deep absorption from neutral hydrogen may indicate that this planet does not have a detectable amount of hydrogen loss, is not losing hydrogen, or has lost hydrogen and other volatiles early in the star’s life. We do not detect a transit and determine a 2σ upper limit on the effective envelope radius of 0.36 R∗ in the red wing of the Lyα line, which is the only portion of the spectrum we detect after absorption by the ISM. We analyze the Lyα spectrum and stellar variability of GJ1132, which is a slowly rotating 0.18 solar mass M dwarf with previously uncharacterized UV activity. Our data show stellar variabilities of 5%–22%, which is consistent with the M dwarf UV variabilities of up to 41% found by Loyd & France. Understanding the role that UV variability plays in planetary atmospheres is crucial to assess atmospheric evolution and the habitability of cooler rocky exoplanets.

Key words: line; profiles – planets and satellites: atmospheres – planets and satellites: individual (GJ 1132b) – stars: activity – stars: low-mass – ultraviolet: planetary systems

1. Introduction

The recent discoveries of terrestrial planets orbiting nearby M dwarfs (Berta-Thompson et al. 2015; Dittmann et al. 2017; Gillon et al. 2017; Bonfils et al. 2018; Ment et al. 2019) provide us with the first opportunity to study small terrestrial planets outside our solar system, and observatories such as the Hubble Space Telescope (HST) allow us to analyze the atmospheres of these rocky exoplanets. Additionally, it is important that we learn as much as we can about these planets as we prepare for atmospheric characterization with the James Webb Space Telescope (JWST; Deming et al. 2009; Morley et al. 2017). JWST will provide unique characterization advantages due to its collecting area, spectral range, and array of instruments that allow for both transmission and emission spectroscopy (Beichman et al. 2014).

M dwarfs have been preferred targets for studying Earth-like planets due to their size and temperature, which allow for easier detection and characterization of terrestrial exoplanets. However, the variability and high UV-to-bolometric flux ratio of these stars makes habitability a point of contention (e.g., Shields et al. 2016; Tilley et al. 2019). It is currently unknown whether rocky planets around M dwarfs can retain atmospheres and liquid surface water or if UV irradiation and frequent flaring render these planets uninhabitable (e.g., Scalo et al. 2007; Hawley et al. 2014; Luger & Barnes 2015; Bourrier et al. 2017b). On the contrary, UV irradiation may boost the photochemical synthesis of the building blocks of life (e.g., Rimmer et al. 2018). We must study the UV irradiation environments of these planets, especially given that individual M stars with the same spectral type can exhibit very different UV properties (e.g., Youngblood et al. 2017), and a lifetime of UV flux from the host star can have profound impacts on the composition and evolution of their planetary atmospheres.

One aspect of terrestrial planet habitability is volatile retention, including that of water in the planet’s atmosphere. One possible pathway of evolution for water on M dwarf terrestrial worlds is the evaporation of surface water and subsequent photolytic destruction of H2O into H and O species (e.g., Jura 2004; Bourrier et al. 2017b). The atmosphere then loses the neutral hydrogen while the oxygen is combined into O2/O3 and/or resorbed into surface sinks (e.g., Wordsworth & Pierrehumbert 2013; Luger & Barnes 2015; Tian & Ida 2015; Shields et al. 2016; Ingersoll 1969). In this way, large amounts of neutral H can be generated and subsequently lost from planetary atmospheres. Studies have shown O2 and O3 alone to be unreliable biosignatures for M dwarf planets because they possess abiotic formation mechanisms (Tian et al. 2014), though they are still important indicators when used with other biomarkers (see Meadows et al. 2018). Understanding atmospheric photochemistry for terrestrial worlds orbiting M dwarfs is critical to our search for life.

1.1. Prior Work

Kulow et al. (2014) and Ehrenreich et al. (2015) discovered that Gliese 436b, a warm Neptune orbiting an M dwarf, has a 56.3% ± 3.5% transit depth in the blueshifted wing of the
stellar Lyα line. Lavie et al. (2017) further studied this system to solidify the previous results and verify the predictions made for the structure of the outflowing gas made by Bourrier et al. (2016). For planets of this size and insolation, atmospheric escape can happen as a result of the warming of the upper layers of the atmosphere, which expand and will evaporate if particles begin reaching escape velocity (e.g., Lammer et al. 2003; Vidal-Madjar et al. 2003; Murray-Clay et al. 2009).

Miguel et al. (2015) find that the source of this outflowing hydrogen is from the H2-dominated atmosphere of Gl 436b, with reactions fueled by OH. Lyα photons from the M dwarf host star dissociate atmospheric H2O into OH and H, which destroy H2/H1 at high altitudes where escape is occurring is formed primarily through dissociation of H2 with contributions from the photolyzed H2O.

Modeling of Gl 436b (Bourrier et al. 2015, 2016) demonstrates that the combination of low radiation pressure, low photoionization, and charge-exchange with the stellar wind can determine the structure of the outflowing hydrogen, which manifests as a difference in whether the light curve shows a transit in the blueshifted region of Lyα or the redshifted region and imprints a specific spectro-temporal signature to the blueshifted absorption. Lavie et al. (2017) used new observations to confirm the Bourrier et al. (2016) predictive simulations that this exosphere is shaped by charge-exchange and radiative braking.

As giant hydrogen clouds have thus been detected around warm Neptunes (see also the case of GJ 3470b; Bourrier et al. 2018a, it opens the possibility for the atmospheric characterization of smaller, terrestrial planets. Miguel et al. (2015) also find that photolysis of H2O also increases CO2 concentrations. For Earth-like planets orbiting M dwarfs, understanding the photochemical interaction of Lyα photons with water is very important for the evolution and habitability of a planet’s atmosphere.

1.2. GJ 1132b

GJ 1132b is a small terrestrial planet discovered through the MEarth project (Berta-Thompson et al. 2015). It orbits a 0.181 M⊕ M dwarf located 12 parsecs away with an orbital period of 1.6 days (Dittmann et al. 2017). Table 1 summarizes its basic properties. This is one of the nearest known transiting rocky exoplanets and therefore provides us with a unique opportunity to study terrestrial atmospheric evolution and composition.

While GJ 1132b is too hot to have liquid surface water, it is important to establish whether this planet and others like it retain substantial atmospheres under the intense UV irradiation of their M dwarf host stars. Knowing whether warm super-Earths such as GJ 1132b regularly retain volatiles such as water in their atmospheres constrains parameter space for our understanding of atmospheric survivability and habitability.

Diamond-Lowe et al. (2018) rule out a low mean molecular weight atmosphere for this planet by analyzing ground-based transmission spectra at 700–1040 nm. By fitting transmission models for atmospheric pressures of 1–1000 mbar and varying atmospheric composition, they find that all low mean molecular weight atmospheres are a poor fit to the data, which is better described as a flat transmission spectrum that could be due to a >10× solar metallicity or >10% water abundance. Whether these results imply GJ 1132b has a high mean molecular weight atmosphere or no atmosphere at all remains to be seen. If we detect a Lyα transit, then this implies UV photolysis of H2O into neutral H and O, leading to outflowing neutral H. The oxygen could recombine into O2 and O3, resulting in a high mean molecular weight atmosphere, and wholesale oxidation of the surface.

This work serves as the first characterization of whether there is a neutral hydrogen envelope outflowing from GJ 1132b as well as an opportunity to characterize the deepest (longest integration) Lyα spectrum of any quiet M dwarf of this mass.

1.3. Solar System Analogs

The atmospheric evolution and photochemistry we evaluate here is similar to what we have seen in Mars and Venus. Much of Mars’ volatile history has been studied in the context of Lyα observations of a neutral H corona that surrounds present-day Mars. Chaffin et al. (2015) use Lyα observations to constrain Martian neutral H loss coronal structure, similar to what we attempt in this work. Indeed, Mars has historically lost H2O via photochemical destruction and escape of neutral H
(Nair et al. 1994; Zahnle et al. 2008), though the solar wind-driven escape mechanisms for Mars are not necessarily the same as what we propose for GJ 1132b in this work.

Venus has long been the example for what happens when a terrestrial planet is irradiated beyond the point of habitability, as is more than likely the case with GJ 1132b. Venus experienced a runaway greenhouse effect, which caused volatile loss and destruction of H\textsubscript{2}O. Kasting & Pollack (1983) study the effects of solar UV radiation on an early Venus atmosphere. They find that within a billion years, Venus could have lost most of a terrestrial ocean of water through hydrodynamic escape of neutral H, after photochemical destruction of H\textsubscript{2}O. GJ 1132b has a higher surface gravity than Venus, which would extend this timescale of hydrogen loss, but it also has a much higher insolation, which would reduce the hydrogen loss timescale. Later in this work, we will estimate the expected maximum mass-loss rate for GJ 1132b based on the stellar Ly\textsubscript{α} profile.

The rest of the paper is organized as follows. In Section 2 we describe the methods of analyzing the Space Telescope Imaging Spectrograph (STIS) data, reconstructing the stellar spectrum, and analyzing the light curves. In Section 3 we describe the transit fit and intrinsic spectrum results. We discuss the results and their implications in Section 4, including estimates of the mass-loss rate from this planet’s atmosphere. In Section 5 we describe what pictures of GJ 1132b’s atmosphere we are left with.

2. Methods

2.1. Hubble STIS Observations

To study the potential existence of a neutral hydrogen envelope around this planet, we scheduled two transit observations of seven orbits each (two observations several hours from midtransit for an out-of-transit measurement and five observations spanning the transit) with the STIS on the HST.\footnote{Cycle 24 GO proposal 14757, PI: Z Berta-Thompson.} We used the G140M grating with the 52 \times 0.05 slit, collecting data in TIME-TAG mode with the far-UV (FUV)-MAMA photon-counting detector. This resulted in 14 spectra containing the Ly\textsubscript{α} emission line (1216 Å), which show a broad profile that has been centrally absorbed by neutral ISM atomic hydrogen.

We reextracted the spectra and corrected for geocoronal emission using the calstis pipeline (Hodge & Baum 1995). The STIS spectrum extraction involved background subtraction, which accounts for geocoronal emission (see Figure 1), leaving us only with the need to model the stellar emission and ISM absorption. We omit data points from both visits that fall within the geocoronal emission signal, wavelengths from both visits that overlapped with strong geocoronal emission and therefore had high photon noise. We thus define our blueshifted region to be \(<-60\ \text{km}\ \text{s}^{-1}\) and our redshifted region to be \(>10\ \text{km}\ \text{s}^{-1}\) relative to the star. One potential source of variability is where the target star falls on the slit. If it fell directly on the slit, then the observed flux will be more than if the star was partially off the slit. To account for this, we scheduled ACQ/PEAK observations at the start of each HST orbit to center the star on the slit and minimize this variability.

In order to analyze the light curves with higher temporal resolution, we used the STIS time-tag mode to split each of the 14 2 ks exposures into four separate 0.5 ks subexposures. This detector records the arrival time of every single photon, which is what allows us to create subexposures in time-tag mode. Each 2D spectrum subexposure was then converted into a 1D spectrum. To do this, we first defined an extraction window around the target spectrum (see Figure 1) and summed up all the flux in that window along the spatial axis. Extraction windows were also defined on either side of the target in order to estimate the background and subtract that from the target window. This results in a noisy line core but eliminates the geocoronal emission signature (Figure 2(a), (b)). These steps were all performed with calstis.

2.2. Stellar Spectrum Reconstruction

With the same spectra used for light-curve analysis, we created a single weighted average spectrum, representing 29.3 ks (8.1 hr) of integration at Ly\textsubscript{α} across 14 exposures (Figure 2(c)). This stacked spectrum was used with the LyaPy modeling program (Youngblood et al. 2016) that uses a nine-dimensional MCMC to reconstruct the intrinsic stellar spectrum assuming a Voigt profile. Modeling observed Ly\textsubscript{α} spectra is tricky because of the neutral ISM hydrogen found between us and GJ 1132. This ISM hydrogen has its own column density, velocity, and line width which creates a characteristic absorption profile within our Ly\textsubscript{α} emission line.

This model takes three ISM absorption parameters (column density, cloud velocity, and Doppler parameter) and models the line core absorption while simultaneously modeling the intrinsic emission, which would give us the resulting observations. Turbulent velocity of the ISM is assumed to be negligible, with the line width dominated by thermal broadening. A fixed deuterium-to-hydrogen ratio of \(1.56 \times 10^{-5}\) (Wood et al. 2004) is also applied to account for the deuterium absorption and emission near Ly\textsubscript{α}. Modeling the ISM parameters required us to approximate the local interstellar medium as a single cloud with uniform velocity, column density, and Doppler parameter. While the local ISM is more complex than this single component and contains two clouds (G, Cet) in the line of sight toward GJ 1132 (based on the model described in Redfield & Linsky 2000), our MCMC results strongly favored the velocity of the G cloud, so we defined the ISM priors based on this cloud (Redfield & Linsky 2000, 2008).

We use uniform priors for the emission amplitude and FWHM, and Gaussian priors for the H I column density, stellar velocity, H I Doppler width, and H I ISM velocity. The H I column density and Doppler width parameter spaces were both truncated in order to prevent the model from exploring physically unrealistic values. For \(N_{\text{HI}}\), we restrict the parameter space to \(10^{16} - 10^{20}\ \text{cm}^{-2}\), based on the stellar distance (12.04 pc) and typical \(n_{\text{HI}}\) values of 0.01–0.1 cm\(^{-3}\) (Redfield & Linsky 2000; Wood et al. 2005). We limit the Doppler width to 6–18 km\(^{-1}\), based on estimates of the Local Interstellar Cloud (LIC) ISM temperatures (Redfield & Linsky 2000).

2.3. Light-curve Analysis

The extracted 1D spectra were then split into a blueshifted mode and redshifted regime, on either side of the Ly\textsubscript{α} core (Figure 2(c)) so that we could integrate the total blueshifted and redshifted flux and create four total light curves from the two visits (Figure 5). Each of these light curves was fitted with a
BATMAN (Kreidberg 2015) light curve using a two-parameter MCMC with the emcee package (Foreman-Mackey et al. 2013). The BATMAN models assume that the transiting object is an opaque disk, which is usually appropriate for modeling planetary sizes. However, we are modeling a possible hydrogen exosphere, which may or may not be disk-like, and which would have varying opacity with radius. For this work, we use the BATMAN modeling software with the understanding that our results tell us the effective radius of a cartoon hydrogen exosphere, which may or may not be disk-like, and which planetary sizes. However, we are modeling a possible hydrogen exosphere, with an assumed spherical geometry.

We fit for $R_e/R_*$ and the baseline flux using a Poisson likelihood for each visit. We use a Poisson distribution because at Lyα, the STIS detector is receiving very few photons. Our log(likelihood) function is:

$$\ln(\text{likelihood}) = \sum_i [d_i \ln(m_i) - m_i - \ln(d_i!)],$$

where $d_i$ is the total (gross) number of photons detected and $m_i$ is the modeled number of photons detected. The photon model is acquired by taking a BATMAN model of in-transit photons and adding the sky photons, which is data provided through the calstis reduction pipeline. Uniform priors are assumed for both $R_e/R_*$ and the baseline flux. We restrict our parameter space to explore only effective cloud radii $>0$, representing physically plausible clouds that block light during transit. By taking simple averages of the light-curve fluxes, we find the ratio of the in-transit flux compared with out-of-transit flux to be $1.01 \pm 0.16$ for the visit 1 red-wing flux and $0.97 \pm 0.13$ for the visit 2 red wing. As both are consistent with no detectable transit, the constraints we obtain from the fitting procedure will represent upper limits on the effective size of any hypothetical cloud.

3. Results

3.1. Spectrum Reconstruction

Figure 3 shows the best-fit emission model with $1\sigma$ models and a corner plot to display the most crucial modeling parameters, with MCMC results shown in Table 2 and Figure 4. This result gives us the total Lyα flux for this M dwarf.

The results of the stellar spectrum reconstruction indicate that there is one component of Lyα flux that is potentially a result of the low signal-to-noise ratio (S/N) regime of these observations. Additionally, our fit indicates that there is one dominant source of ISM absorption between us and GJ 1132—a single cloud with velocity $-3.1 \pm 1.0 \text{ km s}^{-1}$, H1 column density $10^{17.3} \text{ cm}^{-2}$ and Doppler parameter $13.9 \text{ km s}^{-1}$. Our current understanding of the LIC (Redfield & Linsky 2000, 2008) indicates that there should be two clouds, G and Cet in the line of sight of GJ 1132, but our derived $v_H$ is consistent with the velocity of G, which is reported as $-2.73 \pm 0.94 \text{ km s}^{-1}$. We take this to mean that the G cloud is the dominant source of absorption and that we can subsequently reconstruct this spectrum under a single-cloud assumption.

By integrating the reconstructed emission profile, we find a Lyα flux of $2.88_{-0.31}^{+0.42} \times 10^{-14} \text{ erg s}^{-1} \text{ cm}^{-2}$, which gives $f(\text{Lyα})/f(\text{bol}) = 2.9 \pm 0.4 \times 10^{-5}$, where we have calculated the bolometric luminosity of GJ 1132b as:

$$f_{\text{bol}} = \sigma T_{\text{eff}}^4 \left(\frac{R_*}{\text{distance}}\right)^2,$$

where values for the $T_{\text{eff}}$ and $R_*$ were taken from Bonfils et al. (2018) and the distance to the star is taken from Dittmann et al. (2017). Compared with the Sun, which has $f(\text{Lyα})/f(\text{bol}) = 4.6 \times 10^{-6}$ (Linsky et al. 2013), we can see that this M dwarf emits fractionally $6 \times$ more of its radiation in the ultraviolet.
Given the intra-visit stellar variability, we also modeled the average Ly$\alpha$ spectra for visits 1 and 2 separately. All modeled parameters (see Figure 4) were consistent between visits except for the FWHMs, which were different by $3\sigma$, and the total integrated fluxes, which differed by $2\sigma$ ($2.90^{+0.47}_{-0.41} \times 10^{-14}$ erg s$^{-1}$ cm$^{-2}$ for visit 1 and $4.30^{+0.52}_{-0.43} \times 10^{-14}$ erg s$^{-1}$ cm$^{-2}$ for visit 2). For the calculation of mass-loss rates in Section 4.1, we use the integrated flux of the combined reconstructed spectrum (Figure 3).

### 3.2. Light-curve Modeling

The light curves for both visits are shown in Figure 5. MCMC modeling of these light curves resulted in the best-fit parameters shown in Table 3. We report no statistically significant transits, but we can use the modeling results to calculate limits on the hydrogen cloud parameters. To ensure that we were not biasing our results by converting from the measured flux counts to photons s$^{-1}$, we also analyzed the flux-calibrated light curves with Gaussian likelihoods based on pipeline errors and found that the results did not significantly differ from what we present here.

**Table 2**

| Intrinsic Emission Line Model Parameters Taken from MCMC Samples, with 1σ Error Bars |
|---------------------------------|-----------------|
| Line Velocity [km s$^{-1}$]      | 35.23$^{+0.98}_{-0.96}$ |
| log(Amplitude) [erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$] | $-13.25^{+0.08}_{-0.06}$ |
| FWHM [km s$^{-1}$]              | 114.02$^{+4.64}_{-4.99}$ |
| log(H I Column Density) [cm$^{-2}$] | 17.92$^{+0.13}_{-0.15}$ |
| Doppler Parameter (b) [km s$^{-1}$] | 13.91$^{+0.74}_{-1.33}$ |
| H I Velocity [km s$^{-1}$]       | $-3.13^{+1.43}_{-1.18}$ |
| Total Flux [erg s$^{-1}$ cm$^{-2}$] | $2.9 \times 10^{-14}$ |
| Total Flux (1 au) [erg s$^{-1}$ cm$^{-2}$] | $0.18^{+0.03}_{-0.02}$ |

**Note.** Total Flux (1 au) is the flux if it were measured 1 au from the star, whereas the Total Flux is the flux as measured at HST.
3.2.1. The STIS Breathing Effect

There is a well-known intra-orbit systematic that shows up in Hubble STIS observations known as the breathing effect, which can result in a change of amplitude of about 0.1% over the course of an orbit (e.g., Brown et al. 2001; Sing et al. 2008; Bourrier et al. 2017b). This effect is small compared to the photon uncertainty in these observations, but to examine this STIS systematic, we perform our light-curve analysis on the non-time-tagged data. We note that the results are consistent with our time-tagged analysis, so we posit that this effect does not significantly alter our conclusions.

3.3. Stellar Variability

The red wing of our spectral data shows a highly variable stellar Lyα flux over the course of these HST visits and we quantify this variability as a Gaussian uncertainty,

$$\sigma^2 = \sigma^2_{\text{measured}} \sigma^2_{\text{photometric}},$$

where $\sigma_{\text{measured}}$ is our rms noise and $\sigma_{\text{photometric}}$ is the calstis-generated error propagated through our spectral integration. Within one 90 minute HST orbit, we see flux variabilities ($\sigma_f$) of 5%--16% for visit 1 and 7%--18% for visit 2. Among one entire 18-hour visit, variability is 20% for visit 1 and 14% for visit 2 while in the 9 months between the two visits, there is a 22% offset. These results are consistent with the 1%--41% M dwarf UV variability found by Loyd & France (2014).

4. Discussion

With 14 STIS exposures, we have characterized a long-integration Lyα spectrum and furthered our understanding of the intensity of UV flux from this M dwarf. France et al. (2012) find that as much as half of the UV flux of quiescent M dwarfs is emitted at Lyα, so knowing the total amount of flux at this wavelength serves as a proxy for the total amount of UV flux for this type of star. Figure 7 compares the Lyα flux of GJ 1132 derived in this work compared to other known exoplanet host systems. Our measurement of this Lyα flux provides a useful input for photochemical models of haze, atmospheric escape, and molecular abundances in this planet’s atmosphere.

From the redshifted light curves, we can calculate a 2σ upper limit on the radius of this potential hydrogen cloud outflowing from GJ 1132b. We calculate this upper limit (see Figure 6) by taking the joint (visit 1 and visit 2) posterior distributions that resulted from MCMC modeling of these light curves and integrating the CDF to the 95% confidence interval and examining the corresponding $R_p/R_*$, The 2σ upper limit from the redshifted Lyα spectra gives us an $R_p/R_*$ of 0.36. The upper limit $R_p/R_*$ from the blueshifted light curves is 0.62 but given the very low S/N of that data, this is not a meaningful constraint. The redshifted result is an upper limit on the effective radius of a hydrogen coma, and the real coma could be much more diffuse and asymmetric.

4.1. GJ 1132b Atmospheric Loss

In order to connect our results to an upper limit on the possible mass-loss rate of neutral H from this planet’s atmosphere, we follow the procedure outlined in Kulow et al. (2014).

Assuming a spherically symmetric outflowing cloud of neutral H, the equation for mass loss is

$$M_{\text{H I}} = 4\pi r^2 \nu(r) n_{\text{H I}}(r),$$

where $\nu(r)$ is the outflowing particle velocity and $n_{\text{H I}}(r)$ is the number density of H I at a given radius, $r$. For this calculation, we will be examining our 2σ upper-limit radius at which the cloud becomes optically thick, where $(R_p/R_*)^2 = \delta = 0.13$. We assume an $uv$ range of 10--100 km s$^{-1}$, which is the range of the planet’s escape velocity (10 km s$^{-1}$) and the stellar escape velocity (100 km s$^{-1}$).

Kulow et al. (2014) reduce Equation (3) to

$$M_{\text{H I}} = \frac{2\delta R_0 \nu^2}{\sigma_0}$$

with a Lyα absorption cross-section $\sigma_0$ defined as

$$\sigma_0 = \frac{\sqrt{\pi} e^2}{m_e c \Delta \nu_D},$$

where $e$ is the electron charge, $m_e$ is the electron mass, $c$ is the speed of light, $f$ is the particle oscillator strength (taken to be 0.4161 for H I), and $\Delta \nu_D$ is the Doppler width, $b/\lambda_0$, where we use 100 km s$^{-1}$ for $b$, as was done in Kulow et al. (2014).

This gives us an upper-limit mass-loss rate of $M_{\text{H I}} < 0.86 \times 10^9$ g s$^{-1}$ for neutral hydrogen, corresponding to
\[ \dot{M} = \frac{F_{\text{XUV}} \pi R_p^2}{GM_p R_p} = \frac{F_{\text{XUV}} \pi R_p^3}{GM_p} \]

The total \( F_{\text{XUV}} \) is the flux value at the orbit of GJ 1132b. Using our derived Ly\( \alpha \) flux, the \texttt{Lyapyp} package calculates stellar EUV spectrum and luminosity from 100 to 1171 Å based on Linsky et al. (2014). From that EUV spectrum, we then calculate the 5–100 Å XUV flux based on relations described in King et al. (2018).
Assuming 100% efficiency, we obtain an energy-limited neutral hydrogen mass-loss rate of $3.0 \times 10^9$ g s$^{-1}$ estimated from the stellar spectrum reconstruction. This energy-limited escape rate is commensurate with the upper limit we calculate based on the transit depth and stellar properties in the previous section. If we assume a heating efficiency of 1% (based on similar simulations done in Bourrier et al. 2016), then we arrive at a low expected neutral hydrogen loss rate of $3.0 \times 10^7$ g s$^{-1}$, below the level of detectability with these data.

4.2. Simulating H I outflow from GJ 1132b

Figure 8 shows simulation results for neutral hydrogen outflowing from GJ 1132b from the EVaporating Exoplanet code (EVE; Bourrier et al. 2013, 2016). This code performs a 3D numerical particle simulation given stellar input parameters and atmospheric composition assumptions. These simulations were performed using the Ly α spectrum derived in this work, where the full XUV spectrum has been found as described in the previous section. This spectrum is used directly in EVE to calculate the photoionization of the neutral H atoms and calculate theoretical Ly α spectra during the transit of the planet as they would be observed with HST/STIS. In addition, our Ly α spectrum is used to calculate the radiation pressure felt by the escaping neutral hydrogen, which informs the dynamics of the expanding cloud.

EVE simulations were created with the following assumptions: the outflowing neutral hydrogen atoms escape from the Roche lobe altitude ($\sim 5 R_p$) at a rate of $1 \times 10^7$ g s$^{-1}$, modeled as a Maxwellian velocity distribution with upward bulk velocity of 5 km s$^{-1}$ and temperature of 7000 K, resulting in...
a cloud that could absorb upwards of 80% of the flux in the blue wing. However, GJ 1132 has a positive radial velocity, so blueshifted flux falls into the regime of ISM absorption and the signal is lost. Simulations of the in-transit and out-of-transit absorption spectra as they would be observed at infinite resolution by HST are shown in Figure 9. However, the simulations do not rule out that some thermospheric neutral H may absorb some extra flux in the red wing (see Salz et al. 2016 for a justification of simulation parameters). We note that for planets around M dwarfs, the upward velocity may have a strong influence on the extension of the hydrogen coma. The thermosphere is simulated as a 3D grid within the Roche Lobe, defined by a hydrostatic density profile, and the temperature and upward velocity from above. The exosphere is collisionless with its dynamics dominated by radiation pressure.

There might be other processes shaping the exosphere of GJ 1132b (magnetic field, collisions with the stellar wind, the escaping outflow remaining collisional at larger altitudes than the Roche lobe), but for these simulations we take the simplest possible approach based on what we actually know of the system. Finally, we do not include self-shielding effects of H I atoms within the exosphere, as we do not expect the exosphere is dense enough for self-shielding to significantly alter the results.

The integrated Ly$\alpha$ spectrum corresponds with a maximum ratio of stellar radiation pressure to stellar gravity of 0.4, which puts this system in the regime of radiative breaking (Bourrier et al. 2015), which has a slight effect of pushing neutral hydrogen to a larger orbit. However, the gas is not blown away so the size of the hydrogen cloud will increase if we increase the outward particle velocity. Since the exosphere is not accelerated, most of its absorption is close to 0 km s$^{-1}$ in the stellar reference frame, with some blueshifted absorption because atoms in the tail move to a slightly larger orbit than the planet. This indicates that the lack of blueshifted flux in our

![Figure 8](image8.png)  
**Figure 8.** Simulations of the GJ1132 system showing the dynamics of a hypothetical outflowing hydrogen cloud. The left panel shows a top-down view of the system, as a hydrogen tail extends in a trailing orbit. The right panel shows the view from an Earth line of sight, at midtransit.

![Figure 9](image9.png)  
**Figure 9.** EVE simulated absorption spectra in-transit and 4 hr pre-transit. We can see that the only region of significant absorption is at 1215.5 Å, where absorption peaks at about 12% as seen in the bottom panel. While there is a larger expected flux decrease in the blue wing, the signal is largely in the region that the ISM absorbs and our data are too noisy in the blue wing to detect the possible absorption signal seen in the models. The mass-loss rate corresponding to the above model is $1 \times 10^{17}$ g s$^{-1}$.
observations, due to ISM absorption, is a hindrance to fully understanding the possible hydrogen cloud around this planet. The upper-limit cloud size that we quote is based on the observed redshifted flux in a system which is moving away from us at 35 km s\(^{-1}\), so any cloud absorption of flux closer to the line center is outside of the scope of what we can detect.

5. Conclusions

In this work we make the first characterization of the exosphere of GJ 1132b. Until a telescope like LUVOIR (Roberge & Moustakas 2018), these observations will likely be the deepest possible characterization for \(\text{Ly}_\alpha\) transits of this system. If this planet has a cloud of neutral hydrogen escaping from its upper atmosphere, the effective size of that cloud must be less than 0.36 \(R_\oplus\) (7.3 \(R_\oplus\)) in the redshifted wing. The blue wing indicates an upper limit of 0.62 \(R_\oplus\) (12.6 \(R_\oplus\)), though this is a very weak constraint. In addition, we were able to model the intrinsic \(\text{Ly}_\alpha\) spectrum of this star.

This \(\text{Ly}_\alpha\) transit’s upper limit \(R_p/R_\oplus\) implies a maximum hydrogen escape rate of 0.08–0.8 \(\times\) \(10^{27}\) g s\(^{-1}\). If this is the case, GJ 1132b loses an Earth ocean of water between 6 and 60 Myr. Since the mass-loss rate scales linearly with \(\dot{M} \propto M_{\text{atm}} \alpha_{\text{f}}\), the most likely scenario, and thermal emission observations with \(\text{JWST}\) (Morley et al. 2017) would give further insight to the atmospheric composition of GJ 1132b.

4. There might be a giant cloud of neutral hydrogen around GJ1132b based on the EVE simulations, which is undetectable because of ISM absorption. However, if there are other volatiles in the atmosphere we could detect this cloud using other tracers such as carbon or oxygen with \(\text{HST}\) in the FUV, or helium (Spake et al. 2018) with ground-based high-resolution infrared spectrophotographs (see Allart et al. 2018; Nortmann et al. 2018) or with \(\text{JWST}\).

GJ 1132b presents one of our first opportunities to study terrestrial exoplanet atmospheres and their evolution. While future space observatories will allow us to probe longer wavelength atmospheric signatures, these observations are our current best tool for understanding the hydrogen content and possible volatile content loss of this warm rocky exoplanet.

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