Hydrogen Escape from an Earth-size Exoplanet: a Reconnaissance Study

Scientific Category: EXTRA-SOLAR PLANETS

Scientific Keywords: Extra-Solar Planets, Low-Mass And Cool Stars, Planetary Atmospheres, Stellar Activity, Terrestrial Planets

Instruments: STIS

Proprietary Period: 3 months (shorter than default of 12 months)

Proposal Size: Small

Orbit Request	Prime	Parallel
Cycle 23	2	0

Abstract

We just found a small (1.2 Earth radius), warm (roughly 500K) exoplanet transiting a small, nearby M dwarf star. The system's proximity and large planet-to-star radius ratio make it an ideal laboratory for studying the evolution of terrestrial planet atmospheres around M dwarfs, a topic that is important for understanding the habitability of planets around such stars. Depending on how much hydrogen or water is currently being lost from its atmosphere, this new planet might be surrounded by a giant neutral hydrogen exosphere. We would like to measure the size of this cloud, by observing its transit at Lyman-alpha wavelengths with STIS. However, large uncertainties in the strength of the star's Lyman-alpha emission and qualitative depth of the expected transit make it difficult to plan an efficient Hubble program to make such measurements. Here, we propose a two-orbit reconnaissance study to determine how Hubble's precious UV capabilities can be optimally employed to observe this important exoplanet system in Cycle 24. It is possible the planet's exosphere makes a total eclipse of the star at Lyman-alpha; this two-orbit program could detect such an eclipse, which would be the first observation of the exosphere of an Earth-size exoplanet.

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Target Summary:

Target	RA	Dec	Magnitude
LHS-281	10 14 51.8460	-47 09 24.47	V = 13.49, U=16.51, B=15.17, V=13.49, Rc=12.26, Ic=10.69, J=9.245, H=8.666, Ks=8.322

Observing Summary:

Target	Config Mode and Spectral Elements	Flags	Orbits
LHS-281	STIS/FUV-MAMA Spectroscopic G140M (1222)		1
LHS-281	STIS/FUV-MAMA Spectroscopic G140M (1222)		1

Total prime orbits: 2

Rationale for Mid-Cycle Time

We recently discovered an Earth-size planet ($1.2R_\oplus$) transiting a nearby, very small M dwarf. A transit observed by the MEarth-South telescope array on 2015 May 10, after the Cycle 23 deadline, was our first indication of this planet's existence. The planet is a compelling target for atmospheric characterization with Hubble. Observations of the transit at Lyα wavelengths would probe ongoing hydrogen escape from the planet's atmosphere. However, we do not yet know enough to make efficient use of HST to observe this planet in Cycle 24. We do not know if the star is bright enough at Lyα to enable transit observations. We do not know whether the UV transit is extremely deep, blocking most of the star, or shallow. Different answers to these questions would indicate very different strategies for observations in Cycle 24. Here, **we propose a two-orbit program to determine the possibility of observing UV transits of this Earth-size planet, and how best to plan those observations.** If the UV transit is deep, we might detect it with these two orbits. Our strategy, of a short program to assess the Lyα emission from the star before observing transits in a GO program, is the same that produced a high-profile result on GJ 436b (Ehrenreich et al., 2015, Nature). Gathering these observations as soon as possible with a Mid-Cycle program is essential to making optimal use of Hubble's unique UV resources.

Science Justification

For the next decade, the best opportunity we will have to observe the atmosphere of habitable planet will be to detect and study such a planet transiting an M dwarf star. However, we do not know how much such planets retain of their atmospheres in the harsh M dwarf environment, where stellar tides, irradiation, and activity can erode habitable planetary atmospheres more strongly than the Sun-Earth system (Scalo et al., 2007). **Our understanding of the evolution of the atmospheres of terrestrial planets orbiting M dwarfs has not yet been tested by data.**

For some transiting planets, observations at UV wavelengths can directly probe ongoing atmospheric escape. Hydrogen lost from planets can form large neutral halos that absorb strongly at Lyα. Hubble/STIS observations of hot Jupiters have shown these exospheres blocking roughly 10% of their Sun-like host stars (Vidal-Madjar et al., 2003; Lecavelier des Etangs et al., 2012), and recent measurements of the Neptune-sized planet GJ 436b found a large exosphere with a comet-like tail blocking 50% of its early M dwarf star at Lyα (Kulow et al., 2014; Ehrenreich et al., 2015). **Observing the UV-absorbing exosphere of a rocky M dwarf planet would empirically constrain how its atmosphere reacts to the unique low-mass star environment.**

We just discovered an Earth-size planet transiting a nearby M dwarf, a system for which such observations might be possible. Identified by the MEarth Project, GJ 1132b is a $1.2R_\oplus$, $1.6M_\oplus$ planet transiting a nearby, very small M dwarf star (Berta-Thompson et al., accepted to Nature). Its bulk density is consistent with a rocky composition. Whereas other rocky planets with precise masses and radii are heated to >1500K (Motalebi et al., 2015, and references therein), the equilibrium temperature of GJ 1132b is only 530K (assuming efficient recirculation and a Bond albedo of 0.3). This is too hot for the planet to be habitable, but cool enough that GJ 1132b could have retained a substantial volatile atmosphere. Compared to GJ 1214b, the mini-Neptune whose atmosphere has been most intensely observed by Hubble WFC3/IR due to its favorable M dwarf geometry (Berta et al., 2012; Kreidberg et al., 2014), this new planet orbits a star that is the same size (both $0.2R_{\odot}$) but even closer (12.0 pc vs. 14.5 pc). **The system's large planet-to-star radius ratio and close proximity greatly enhance the ease with which GJ 1132b's atmosphere can be observed, compared to other Earth-size exoplanets (Figure 1).**

Ultimately, we want to use STIS to measure the size of GJ 1132b's Lyα exosphere. However, two key questions must be answered before we can justify the heavy investment required to observe UV transits. Here, **we propose a two-orbit reconnaissance study that will determine (a) whether a program in Cycle 24 could observe GJ 1132b's exosphere and (b) how best to plan such a program.** Answering these questions now will help make optimal use of Hubble's UV capabilities to observe this Earth-size planet.

Is GJ 1132 bright enough at Lyα to enable transit observations? Existing data indicate the star is mildly magnetically active. MEarth-South photometric modulations indicate the presence of magnetic starspots, but the long rotation period (125 days) suggests low field strengths. HARPS spectra show Ca II H emission, but with weak intensity. The Hα line is seen in absorption; the presence of H atoms excited to the n=2 level requires chromospheric heating and implies at least some Lyα emission above the photosphere.

Even with these qualitative activity indicators, it is difficult to quantitatively predict the Lyα flux. To determine whether GJ 1132 emits enough Lyα photons for transits to be detectable, we must observe it directly. The duration of the planet's optical transit is 46 minutes, roughly one HST orbital visibility window. **Detecting the UV transit will require, at a minimum, that the star's Lyα emission line is sufficiently bright to be detected in one HST orbit. We will use one of our requested two orbits to measure the stellar spectrum at Lyα.** We will schedule this measurement far from times of transit, to ensure it is not corrupted by the planet's exospheric absorption.

GJ 1132 has a heliocentric velocity of +35 km s^{-1}, indicating ISM absorption will be stronger blueward of the rest-frame Lyα core. We need to know how much of this blue side of the line makes it to Earth unobscured, because the planetary exosphere is predicted to show the largest transit signatures in the Lyα blue wing, due to radiation pressure and/or stellar wind accelerating gas away from the star (Figure 2). The ISM is difficult to predict along any line-of-sight; its patchiness could be responsible for the very different observed Lyα spectra of GJ 436 (bright) and GJ 1214 (undetected in four orbits). Without observing GJ 1132 directly, we cannot know what to expect.

Does GJ 1132b have an extremely deep Lyα transit? When the warm Neptune GJ 436b is in front of its star, it blocks 50% of starlight in the blue wing of the Lyα line, indicating an extended exosphere with a large comet tail (Figure 2; Ehrenreich et al., 2015). The orbit of GJ 436b only grazes the star, but an equatorial transit would likely have blocked close to 100% of the $0.44R_\odot$ radius star. Models of this system indicate this transit is so deep because radiation pressure on the exospheric gas is weaker than gravity, allowing a large cloud of hydrogen to persist co-moving with the planet. For GJ 1132b, the transit is more equatorial (impact parameter of 0.46 ± 0.11), the star is smaller, and the relative strength of radiation pressure to gravity might be even weaker than GJ 436. Therefore, **the exosphere of GJ 1132b could potentially create a total Lyα eclipse of the star.**

The escape rate of hydrogen from GJ 1132b's atmosphere is unknown, so it is impossible to predict the depth of its transit *a priori*. The planet's mass and radius (Figure 1) do not rule out a residual H/He atmosphere that could fuel this escape. Alternatively, if the planet's outer envelope is depleted of primordial H/He but rich in water, the high stellar irradiation (19×Earth) keeps it in a runaway greenhouse state, with water extending to the upper atmosphere where it can be dissociated and its hydrogen can escape. The mass loss rate depends on the star's unmeasurable EUV luminosity; the best way to estimate this would be to use Lyα (see above) and use it as a proxy (Linsky et al., 2014). The unknown initial hydrogen/water reservoir and past/present stellar UV luminosity make it difficult to predict how much hydrogen the planet's atmosphere contains and how much it is currently losing.

Yet, for planning observations of the Lyα transit, it is important to know whether we expect such a deep eclipse or a much shallower one. If the eclipse is deep, its duration will also be long. Early Lyα observations of GJ 436b extended only 2.5 hours after the optical mid-transit (PI Ehrenreich, GO/12965), but modeling of those deep eclipses indicates the Lyα transit of the long tail of escaping hydrogen probably lasts 20 hours beyond the optical transit, which will soon be observed (PI Ehrenreich, GO/14222). **For GJ 1132b, knowing whether the Lyα transit is deep and long or shallow and short influences how transit observations could be gathered most efficiently (Figure 3). We will schedule one of our two orbits during transit; by comparing this in-transit measurement to the out-of-transit measurement, we will determine the depth of the Lα transit and how to plan Cycle 24 observations to capture its full duration.**

Additional Science – The UV Flux at the Top of the Planet's Atmosphere Lyα often dominates the UV energy budget for planets orbiting mid-M dwarfs and influences planets' atmospheric abundances, temperature structure, and cloud content through photochemistry in the upper atmosphere (Morley et al., 2013; Miguel et al., 2015). Regardless of the possibility of detecting the planetary exosphere, **this Mid-Cycle program's measurement of the stellar Lyα flux will provide a key input to photochemical models of GJ 1132b's atmosphere.** Our team has experience in correcting for ISM absorption, to determine the intrinsic Lyα flux seen by the planet.

Conclusion Fewer than 500 star systems are more nearby than GJ 1132. It is likely that GJ 1132b is one of the easiest-to-observe transiting Earth-size exoplanets we will ever know. For the foreseeable future, the Hubble Space Telescope provides our only option to observe this system in the UV. Getting the most out of these precious capabilities requires that we act quickly, and this Mid-Cycle program makes a first step in that direction.

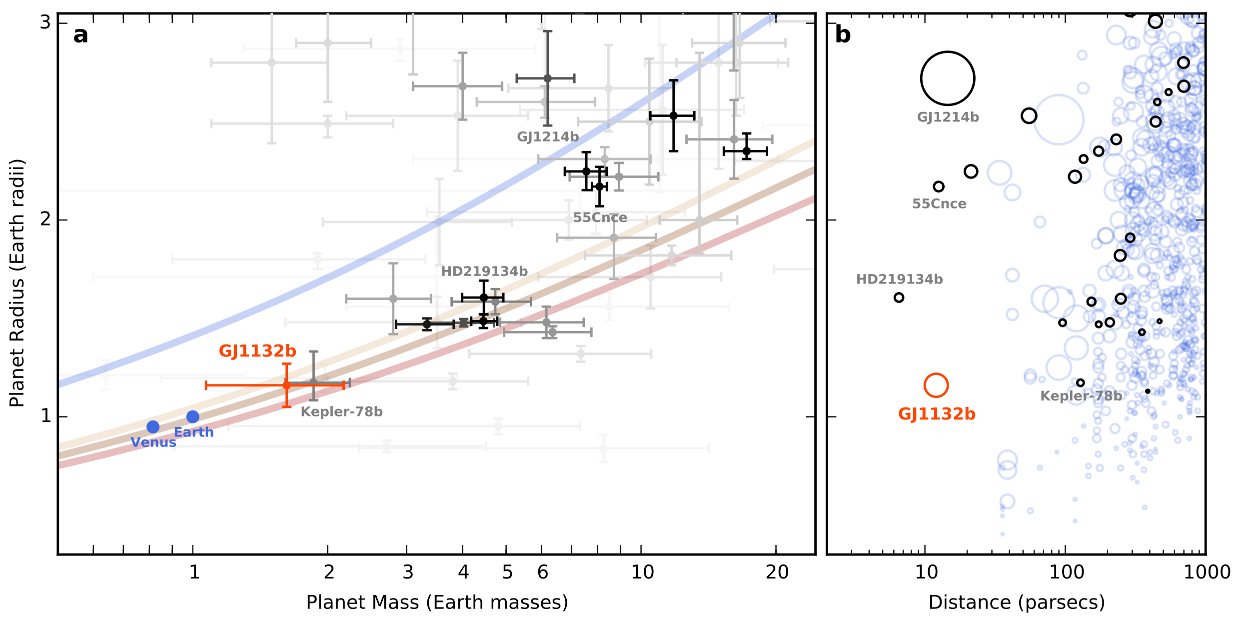

Figure 1: GJ 1132b in the context of other planets. *Left:* Its mass and radius are similar to Earth's. Other planets with measured masses and radii are shown for comparison, with opacities inversely proportional to the square of the planets' fractional density uncertainties. Mass-radius models are shown for pure water planets and simplified two-layer rocky planets with 0%, 25%, and 50% of their mass in Fe cores. *Right:* Among transiting planets with masses measured to better than 2.5σ (*black*) or not (*blue*), GJ 1132b is nearer than other Earth-size planets. Circle areas are proportional to planets' optical transit depths, and GJ 1132b's depth of 0.3% is much deeper than other planets known to be rocky (figure from Berta-Thompson et al., submitted).

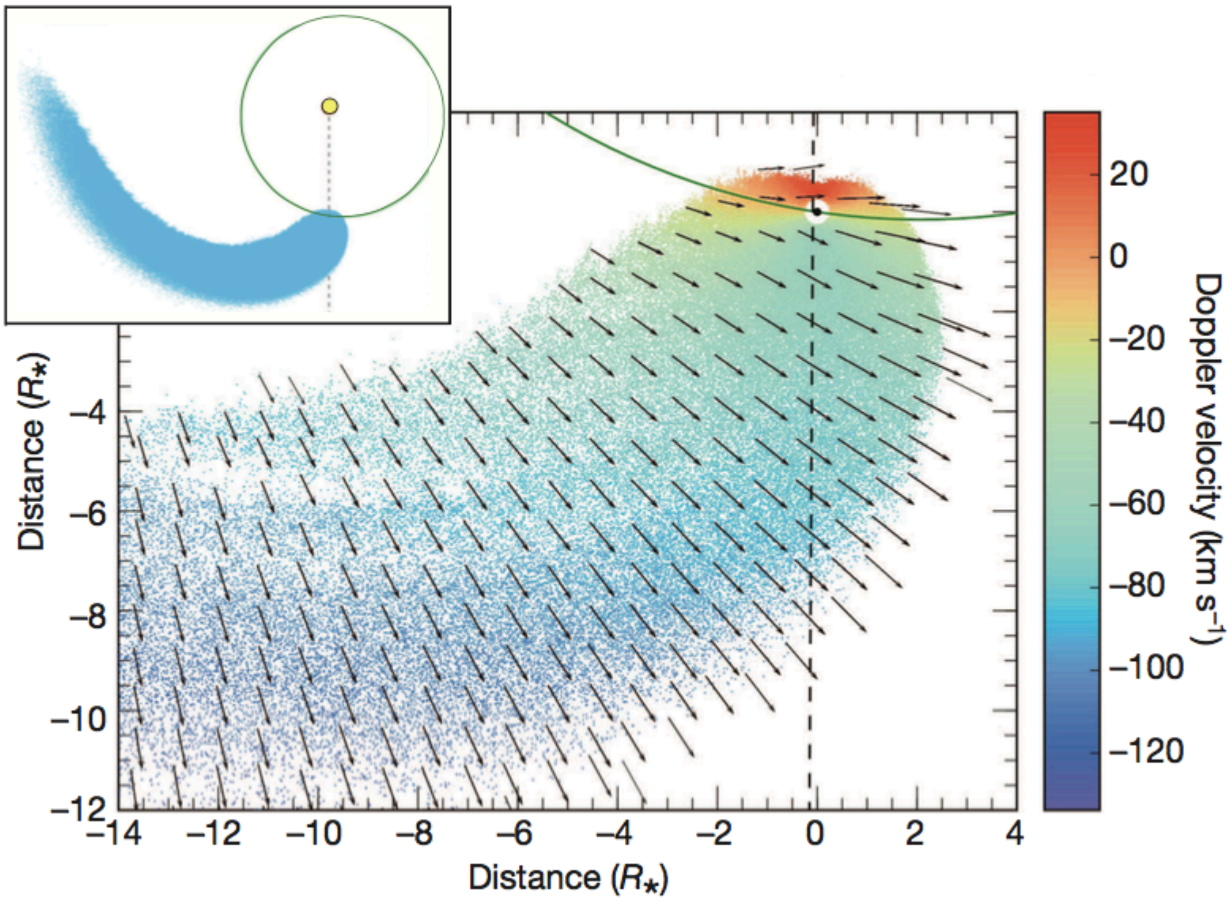

Figure 2: The large exospheric comet tail of the Neptune-size planet GJ 436b. In this top-down view of a simulation matched to STIS observations of the planet's Lyα transit, neutral hydrogen is shown escaping from the planet (the black dot in the upper right corner of the main panel), forming a comet-like cloud, and absorbing about 50% of the star's light in the blueshifted wings of the Lyα line. If GJ 1132 has significant hydrogen in its atmosphere, it could have a UV transit as deep as GJ 436b (figure from Ehrenreich et al. 2015).

How does this Mid-Cycle program inform Cycle 24 UV observations of GJ 1132?

	The in-transit orbit tells us if the planetary exosphere blocks… …most of star.	…a small fraction of the star.
The out-of-transit orbit tells us if the star is…	The exosphere has a large coma + tail. Transits are deep (up to 100%) and long (multiple HST orbits).	The exosphere is compact. Transits are shallow (<10%) and short (about one HST orbit).
…bright at Lyα.	We should plan few transits because the signal is so large. Visits should be as long as possible and scheduled at multiple phases to probe the full duration of the Lyα transit.	We should plan more transits because signal is weak. Visits can be short because each Lyα transit spans only one HST orbital visibility window.
…faint at Lyα.	Although the Lyα flux may be faint, the lines of other elements in the near-UV (e.g. Mg, Fe) might not be. We should schedule observations at these complementary wavelengths to provide complete inputs for photochemical models of the planet's atmosphere and clouds, and potentially to search for planet-induced absorption by these elements.	

Figure 3: Possible outcomes of this Mid-Cycle program for future observations of GJ 1132b.

Description of the Observations

We propose to observe the star GJ 1132 at Lyα with two visits of one HST orbit each. One visit will be performed far from the planet transit, to measure the intrinsic stellar Lyα emission. The other visit will be performed at the time of the transit, to assess the presence of a hydrogen envelope around the planet. In each case, we estimate that one HST orbit will be enough to perform these objectives. All observations will make use of the STIS/FUV-MAMA and the G140M grism, centered on a wavelength of 1222Å. These Lyα observations cannot be made from the ground; they can be achieved only with HST.

Scheduling Requirements

The program must be completed before 2016 March 1, so the observations can be used to inform Cycle 24 proposals. One of the visits must be scheduled during a transit of the planet. Transits occur every 1.62 days and last 46 minutes each. We require a PHASE restriction with a margin of roughly 30 minutes per planetary period, to ensure substantial overlap between the HST orbital visibility window and the transit. With the APT Phase II tool, we verified there are many opportunities this in-transit orbit. The other visit must be scheduled away from transits, to minimize potential absorption by the exosphere. The PHASE restriction for this out-of-transit orbit is much looser (about 0.4 out of every 1.6 days), which provides plenty of opportunities for observations.

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