Hydrogen Escape from a Rocky Earth-Size Exoplanet

Scientific Category: Extrasolar Planets and Planet Formation

Scientific Keywords: Exoplanet Host Stars, Extra-Solar Planets, Planetary Atmospheres, Terrestrial Planets, Transits

Instruments: STIS

Proprietary Period: 12 months

Proposal Size: Small UV Initiative: Yes

Orbit Request	Prime	Parallel
Cycle 24	14	0

Abstract

Planets transiting M dwarfs offer our best opportunities to observe the atmospheres of potentially habitable planets outside the Solar System. Models predict that M dwarfs can significantly erode their planets' atmospheres, but no observations yet exist to investigate this atmospheric escape. GJ1132b is a warm, rocky, Earth-size planet transiting a star that is both very nearby (12pc) and very small (0.21 solar radii). Here, we propose to use GJ1132b as a laboratory to examine the process of hydrogen escape from terrestrial planets, a topic that is important for understanding the evolution of habitable worlds. We will use STIS to observe two transits of GJ1132b at Lyman-alpha wavelengths, to measure the size of the neutral hydrogen cloud escaping from the planet. Such a cloud might be fed by the dissociation of trace amounts of water or hydrogen halides in the planet's upper atmosphere. In a Cycle 23 pilot study, we proved the star is bright enough at Ly-alpha to serve as a backlight for these observations, and we tentatively detected a 40% flux decrement when the planet was in front the star. GJ1132b is subject to less radiation pressure than the comet-tailed exoplanet Gl436b; this allows neutral hydrogen to develop into an inflated coma and leading arm, with substantial absorption before and during the time of optical transits. These observations would provide the first constraints on atmospheric escape from an Earth-size planet around an M dwarf, and they make use of Hubble's precious UV capabilities to inform future JWST atmospheric observations of GJ1132b and other rocky planets.

Investigators:

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Number of investigators: 8

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Target Summary:

Target	RA	Dec	Magnitude
LHS-281	10 14 51.8460	-47 09 24.47	V = 13.49 +/- 0.03, 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)		10 (5x2)
LHS-281	STIS/FUV-MAMA Spectroscopic G140M (1222)		4 (2x2)

Total prime orbits: 14

■ Scientific Justification

TESS (Ricker et al., 2015) should find transiting rocky planets in the habitable zones of nearby small M dwarfs (Sullivan et al., 2015), and JWST should be able to observe the atmospheres of some of these planets (Deming et al., 2009). However, as exoplanet host stars, M dwarfs are very different from Sun-like stars (Scalo et al., 2007; Tarter et al., 2007). We are not yet prepared to interpret atmospheric observations of habitable planets that transit them. Models predict that planetary atmospheres will be significantly sculpted by prolonged exposure to enhanced bolometric, XUV, and particle flux from young active M dwarfs (Segura et al., 2005; Owen & Jackson, 2012; Luger et al., 2015), but our understanding of the atmospheres of terrestrial M dwarf planets has not yet been confronted by data.

Here, **we propose to use STIS to observe transits of the warm rocky planet GJ1132b at Lyα wavelengths**. By probing the tenuous cloud of neutral hydrogen streaming away from the planet, these transits would provide a snapshot of the rate at which a terrestrial planet's atmosphere is evaporating to space, and the first empirical constraints on the ongoing evolution of a terrestrial planet around an M dwarf. This system offers a unique laboratory to study the physical properties of the ubiquitous Earth-sized M dwarf planets revealed by Kepler (Dressing & Charbonneau, 2015), and it provides valuable context toward future observations of terrestrial planets with JWST.

GJ1132b is an Easy-to-Observe Transiting Earth-size Planet. Using the MEarth Observatory (Irwin et al., 2015), we discovered GJ1132b and determined it to be a $1.2R_\oplus$ exoplanet transiting a $0.21R_\odot$ star once every 1.6 days (Berta-Thompson et al., 2015). Radial velocities confirm GJ1132b to be consistent with a rocky composition, with a mass of $1.6M_\oplus$ and density of 6 g/cm^3, as expected for its small size (Rogers, 2015; Wolfgang et al., 2015). Thanks to the low luminosity of its host star, GJ1132b has an equilibrium temperature of only 530K (assuming efficient heat circulation and a Bond albedo of 0.3). This is cooler than most other rocky exoplanets with measured densities, the majority of which are heated to $> 1500K$. The star GJ1132 is among the smallest of known exoplanet hosts, and at 12pc it is closer than any other Earth-size exoplanet system (Figure 1). **Thanks to its proximity and large planet-to-star radius ratio, GJ1132b offers the first opportunity for Hubble to make interesting measurements of the atmosphere of a rocky planet outside the Solar System.** GJ1132b is a likely target for future atmospheric characterization with JWST and may be among the best rocky exoplanet targets for decades to come; TESS is predicted to find only about 10 planets closer than 12pc, with radii ranging from $1R_\oplus$ to $3R_\oplus$ (Sullivan et al., 2015).

GJ1132b's Atmosphere is Sculpted by Its Star. Based on its 125 day rotation period, the star GJ1132 is likely about 5 Gyr old (Newton et al., 2015). In its early history, the high bolometric, XUV, and particle fluxes from its inflated and active young M dwarf would have eroded much of its atmosphere (Lammer et al., 2007; Murray-Clay et al., 2009; Owen & Wu, 2015; Luger & Barnes, 2015). However, it is possible GJ1132b's atmosphere still contains

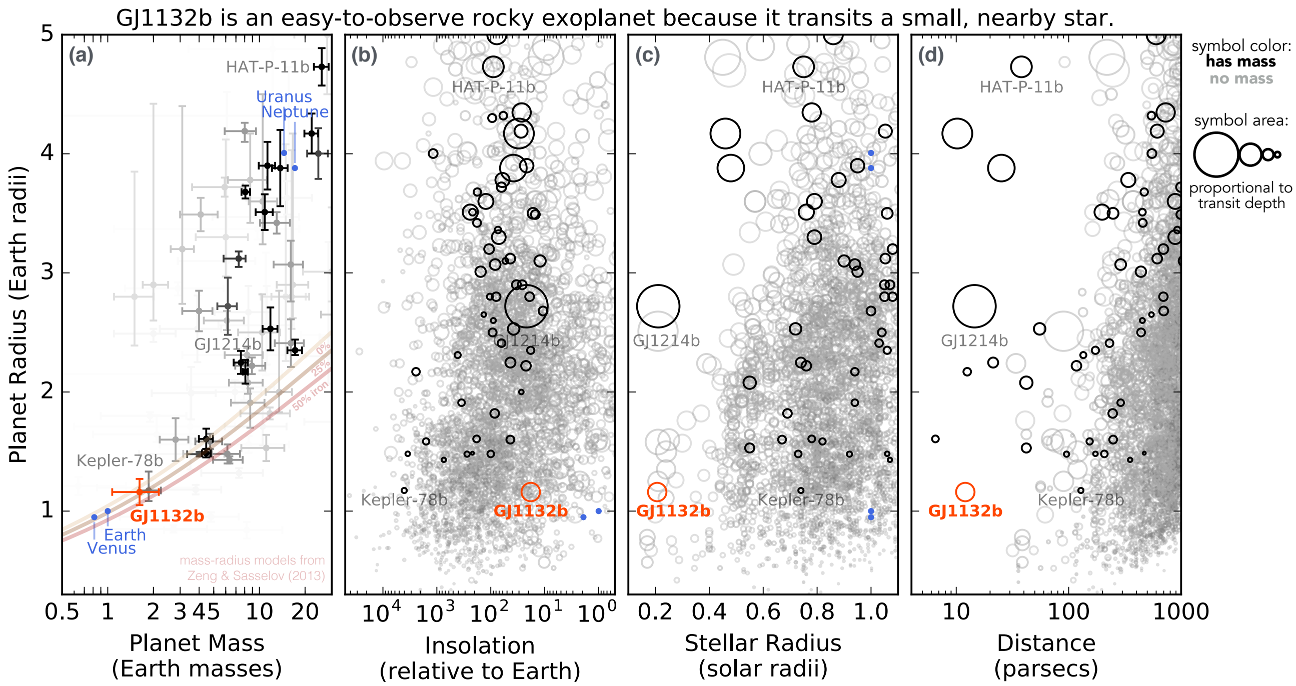

Figure 1: GJ1132b's mass and radius are similar to Earth's, and consistent with mass-radius models for rocky planets (a). It is smaller and cooler than other planets with well-measured masses and radii (b), but atmospheric characterization is possible for GJ1132b because it transits a star that is both small (c) and nearby (d). **GJ1132b provides the best opportunity for UV observations with Hubble to probe hydrogen escape from an Earth-size planet.**

some H-bearing molecules. The planet's initial volatile budget is unknown (Carter-Bond et al., 2012) and might have been very large, if for example if it were the eroded remnant of a planet that formed beyond the snow-line (Luger et al., 2015). Even if the atmosphere were lost, later oxidation of the metallic core and mantle outgassing could replenish it with H-rich gases (Elkins-Tanton & Seager, 2008; Schaefer et al., 2012). The delicate balance of atmospheric escape and outgassing will ultimately determine the habitability of habitable-zone planets around M dwarfs like GJ1132, so opportunities to observe either of these processes are valuable.

STIS Lyα Transits Probe Hydrogen Escape from the Exosphere With Hubble, we can observe ongoing late-stage hydrogen escape from GJ1132b. Hydrogen escaping from planets can form large neutral halos that absorb strongly at Lyα (Figure 2). Hubble/STIS observations of hot Jupiters have shown these exospheres can block 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 Gl436b 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). If GJ1132b's atmosphere is currently losing hydrogen, Hubble observations could detect its Lyα absorption signature.

Gl436b is a gas-rich planet (Adams et al., 2008) and has a deep reservoir of H_2 that can continuously feed H escape. We do not know whether GJ1132 has substantial H_2, but even without it there would exist a plausible long-term source for H atoms. Venus has lost most of its water, but yet it has a resonantly scattered Lyα corona (Chaufray et al., 2012). The neutral hydrogen making up this corona is populated by the dissociation of the remaining trace amounts of H_2O in the upper atmosphere, as well as HCl, HF, and HDO (Bertaux et al., 2007). If GJ1132b is similar to Venus, these molecules could steadily feed an escaping cloud of neutral H that might be detected in Lyα transits.

We May have Already Detected Lyα Absorption from GJ1132b. We ran a Cycle 23 Mid-Cycle pilot study to assess the feasibility of such observations (GO-14462). As the UV spectra of slowly rotating, low-mass M dwarfs like GJ1132 are poorly understood (Youngblood et al., 2016), we did not know whether the star emitted enough light to serve as a backlight for Lyα transits. In our two-orbit program, we confirmed that the stellar Lyα is bright enough to allow transit observations, and we also detected tentative evidence for neutral hydrogen absorption from the planet's escaping exosphere (Figure 3). The ISM absorbs most of stellar line blueward of its core, but the red wing of the Lyα appears to show a 40% decrease (4σ significance) when the planet is in front of the star.

Gl436b showed absorption only in the blue wing of the Lyα line (Ehrenreich et al., 2015). Bourrier et al. (2015) interpreted this as due to Lyα radiation pressure accelerating neutral H away from the star. Preliminary estimates using our out-of-transit spectrum (and a rough correction for ISM absorption) suggest the influence of radiation pressure is less important for GJ1132b, thereby allowing the development of a more inflated coma and a leading arm of material at redshifted velocities (Figure 2). In this picture, the larger coma counteracts the lower expected mass-loss rate (due to GJ1132b's lower irradiation and H_2-content), allowing GJ1132b to show Lyα transits as deep as Gl436b. Here, we propose to properly observe Lyα transits of GJ1132b, to detect and map the cloud of neutral hydrogen escaping from its atmosphere. These data would provide a snapshot of atmospheric escape processes at late times, to inform theories of terrestrial planet atmospheric evolution.

We Will Measure Lyα Variability for a Benchmark 0.2$M_\odot$ M Dwarf An alternative explanation for the flux decrement is simply that the star is variable at Lyα. The Lyα flux from Gl436 (0.4$M_\odot$) was stable over years (Ehrenreich et al., 2015). However, we have little context for stars like GJ1132 that are less massive (0.18$M_\odot$) and very slowly rotating (125 days); no long-term Lyα variability studies have been conducted for such stars[1]. If we do not detect Lyα transits, we will at least characterize the variability of the star at Lyα, data which will serve as crucial modeling inputs for photochemistry in the atmospheres of GJ1132b and other planets transiting very low-mass M dwarfs (see Miller-Ricci Kempton et al., 2012; Rugheimer et al., 2015).

[1] GJ1214 was observed twice with STIS at Lyα, in GO-12165 and GO-13650, but acquisition failed during one observation.

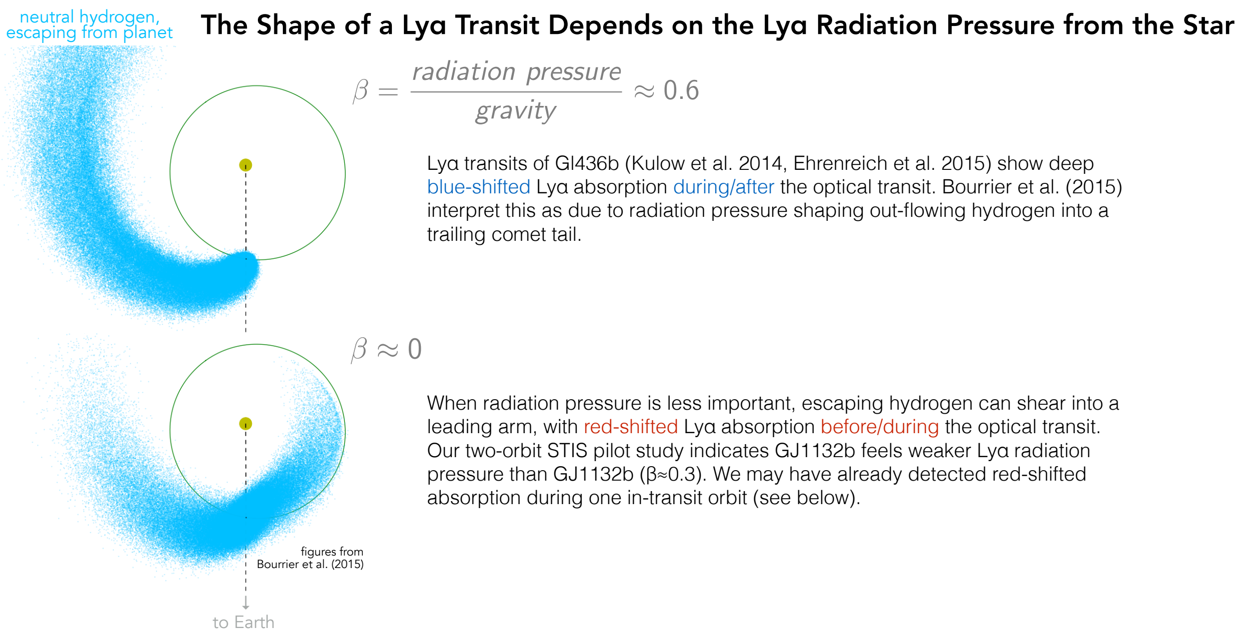

Figure 2: Clouds of neutral hydrogen escaping from a planet's exosphere can exhibit eclipses at Lyα that are much deeper than the optical transit (even up to 100%). We hope to map the cloud surrounding GJ1132b, to probe the rate at which dissociated H_2 or H_2O is lost from the planet.

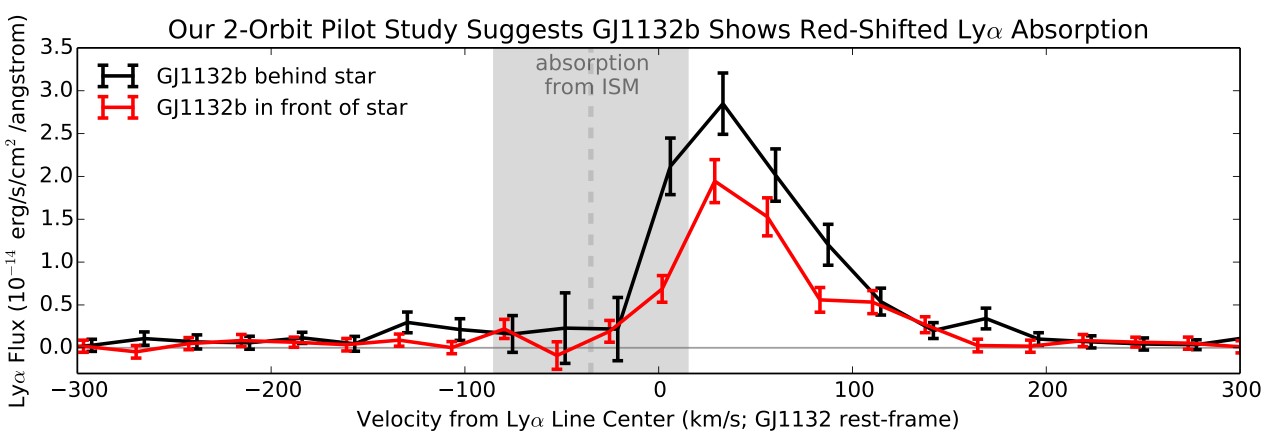

Figure 3: We observed GJ1132 at Lyα with a Mid-Cycle progam (GO-14462) with one out-of-transit orbit and one in-transit orbit, to determine (a) whether the star emits detectable Lyα flux and (b) whether there was any indication for deep eclipses. We detected the star, and found it was significantly fainter during the in-transit orbit. Here, we propose observations to confirm whether this deficit is due to absorption by the planet's exosphere or to stellar variability.

Description of the Observations

We propose to gather STIS/FUV-MAMA multiwavelength light curves of GJ1132b at Lyα. These data will be sensitive to large clouds of neutral hydrogen surrounding the planet, and the rate at which hydrogen is escaping from the atmosphere.

We Will Use Proven Methods. We will use the G140M grism, centered on a wavelength of 1222Å. We use sky background light measured along the slit to subtract the geocoronal Lyα, so we must use STIS instead of COS. To balance throughput and velocity resolution, will use the 52"×0.1" aperture. We will perform ACQ/PEAK acquisitions at the start of each orbit. These methods are similar to those we used in previous UV eclipse observations (Ehrenreich et al., 2015).

We Will Observe Two Transits at Lyα. Based on our two extant spectra, we estimate that we will be able to measure the integrated flux in the red wing of the Lyα line (0 to +130km/s in Figure 3) to a precision of 8% in a single HST orbit (2095s of exposure, after acquisition overheads). Models consistent with the 40% red-shifted eclipse show maximum absorption before and during the planet's solid-body transit, and typical durations of several hours. To best span the predicted eclipse shape, and given the constraints of the SAA, we would schedule each transit observation as a visit consisting of five HST orbits, with the visibility window of the fourth orbit coinciding with the time of the optical transit. Although a single visit would be sufficient to detect a 40% eclipse, it is sensible to observe two transit observations to ensure any eclipse phenomenon we see repeats during each planetary transit.

We Will Gather Unobscured Reference Spectra Far from Transit We do not know the full duration of Lyα eclipses, as gas might persist over a range of orbital phases (Figure 2). As a cross-check, for each transit we will schedule a two-orbit visit when the planet and its gas cloud are behind the star, as unobscured reference spectra. We will gather these reference visits soon after the transit observations, to guard against variability in the stellar Lyα flux. With two 5-orbit transits and two 2-orbit reference visits, we request a total of 14 HST/STIS orbits.

Only HST Can Conduct these Observations. The STIS Lyα observations are not possible from the ground, or from any other existing or planned space telescope. This program makes timely use of HST's waning UV capabilities, and will provide critical context for future atmospheric observations of GJ1132b with JWST.

Special Requirements

Two STIS visits, of five orbits each, must be scheduled at times of transit. Transits occur every 1.62 days and last 46 minutes in the optical (comparable to one HST visibility window). We implement a PHASE constraint with a margin of roughly 10 minutes per planetary period, to ensure optimal overlap between the in-transit orbit and the optical transit. As the expected UV duration is longer than the optical transit, this phase constraint could be relaxed if it proves too restrictive for scheduling. The two other STIS visits, of two orbits each, must be scheduled at times far from transit, to gauge the unobscured Lyα flux level from the star. These reference visits should be scheduled one half orbital period (0.8 days) after each transit.

■ Coordinated Observations

GJ1132 shows photometric variability due to starspots, with modulations that have a peak-to-peak amplitude of about 1% in the 715-1000nm bandpass. To provide greater context for these Lyα observations, we will continue to monitor the star's brightness both between and during transits, using the MEarth telescopes (Irwin et al., 2015). We will use these data to test whether Lyα flux is correlated with photospheric starspot features. We have not detected optical-light flares from GJ1132, but we will attempt simultaneous monitoring of STIS visits, in case Lyα does show significant variability.

■ Justify Duplications

We observed GJ1132 with STIS/FUV-MAMA in Cycle 23, with one orbit during GJ1132b's transit and one orbit far from transit. Those data were gathered as a pilot study for this program, in which we propose to observe multiple complete transits, with denser sampling.

This proposal explores ongoing hydrogen escape from GJ1132b's atmosphere. We are also submitting another Cycle 24 proposal using WFC3 to constrain the current hydrogen content of the planet's atmosphere. Together, these proposals provide complementary views of this important planet's atmosphere. However, they are sufficiently distinct that awards made to either program individually would be scientifically valuable.

References

Adams, E. R., Seager, S., & Elkins-Tanton, L. 2008, ApJ, 673, 1160
Berta-Thompson, Z. K., et al. 2015, Nature, 527, 204
Bertaux, J.-L., et al. 2007, Nature, 450, 646
Bourrier, V., Ehrenreich, D., & Lecavelier des Etangs, A. 2015, A&A, 582, A65
Carter-Bond, J. C., O'Brien, D. P., & Raymond, S. N. 2012, ApJ, 760, 44
Chaufray, J.-Y., Bertaux, J.-L., Quémerais, E., Villard, E., & Leblanc, F. 2012, Icarus, 217, 767
Deming, D., et al. 2009, PASP, 121, 952
Dressing, C. D., & Charbonneau, D. 2015, ApJ, 807, 45
Ehrenreich, D., et al. 2015, Nature, 522, 459
Elkins-Tanton, L. T., & Seager, S. 2008, ApJ, 685, 1237
Irwin, J. M., Berta-Thompson, Z. K., Charbonneau, D., Dittmann, J., Falco, E. E., Newton, E. R., & Nutzman, P. 2015, in 18th Cambridge Workshop on Cool Stars, ed. G. T. van Belle & H. C. Harris, 767–772

Kulow, J. R., France, K., Linsky, J., & Loyd, R. O. P. 2014, ApJ, 786, 132
Lammer, H., et al. 2007, Astrobiology, 7, 185
Lecavelier des Etangs, A., et al. 2012, A&A, 543, L4
Luger, R., & Barnes, R. 2015, Astrobiology, 15, 119
Luger, R., Barnes, R., Lopez, E., Fortney, J., Jackson, B., & Meadows, V. 2015, Astrobiology, 15, 57
Miller-Ricci Kempton, E., Zahnle, K., & Fortney, J. J. 2012, ApJ, 745, 3
Murray-Clay, R. A., Chiang, E. I., & Murray, N. 2009, ApJ, 693, 23
Newton, E. R., Irwin, J., Charbonneau, D., Berta-Thompson, Z. K., Dittmann, J. A., & West, A. A. 2015, ArXiv e-prints
Owen, J. E., & Jackson, A. P. 2012, MNRAS, 425, 2931
Owen, J. E., & Wu, Y. 2015, ArXiv e-prints
Ricker, G. R., et al. 2015, Journal of Astronomical Telescopes, Instruments, and Systems, 1, 014003
Rogers, L. A. 2015, ApJ, 801, 41
Rugheimer, S., Kaltenegger, L., Segura, A., Linsky, J., & Mohanty, S. 2015, ApJ, 809, 57
Scalo, J., et al. 2007, Astrobiology, 7, 85
Schaefer, L., Lodders, K., & Fegley, B. 2012, ApJ, 755, 41
Segura, A., Kasting, J. F., Meadows, V., Cohen, M., Scalo, J., Crisp, D., Butler, R. A. H., & Tinetti, G. 2005, Astrobiology, 5, 706
Sullivan, P. W., et al. 2015, ApJ, 809, 77
Tarter, J. C., et al. 2007, Astrobiology, 7, 30
Vidal-Madjar, A., Lecavelier des Etangs, A., Désert, J.-M., Ballester, G. E., Ferlet, R., Hébrard, G., & Mayor, M. 2003, Nature, 422, 143
Wolfgang, A., Rogers, L. A., & Ford, E. B. 2015, submitted to ApJ (arxiv:1504.07557)
Youngblood, A., et al. 2016, accepted to ApJ (arxiv:1604.01032)