TRANSIT SURVEYS FOR EARTHS IN THE HABITABLE ZONES OF WHITE DWARFS

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ABSTRACT

To date the search for habitable Earth-like planets has primarily focused on nuclear burning stars. I propose that this search should be expanded to cool white dwarf stars that have expended their nuclear fuel. I define the continuously habitable zone of white dwarfs, and show that it extends from ≈ 0.005 to 0.02 AU for white dwarfs with masses from 0.4 to 0.9 $M_\odot$, temperatures less than $\approx 10^4$ K, and habitable durations of at least 3 Gyr. As they are similar in size to Earth, white dwarfs may be deeply eclipsed by terrestrial planets that orbit edge-on, which can easily be detected with ground-based telescopes. If planets can migrate inward or reform near white dwarfs, I show that a global robotic telescope network could carry out a transit survey of nearby white dwarfs placing interesting constraints on the presence of habitable Earths. If planets were detected, I show that the survey would favor detection of planets similar to Earth: similar size, temperature, rotation period, and host star temperatures similar to the Sun. The Large Synoptic Survey Telescope could place even tighter constraints on the frequency of habitable Earths around white dwarfs. The confirmation and characterization of these planets might be carried out with large ground and space telescopes.

Subject headings: astrobiology — binaries:eclipsing — eclipses — planetary systems — planets and satellites:detection — white dwarfs

1. INTRODUCTION

The search for habitable planets has focused on stars similar to the Sun as it is the sole example we have of a star with a habitable planet, and nuclear burning provides a long-lived source of energy (Kasting et al. 1993; Lunine et al. 2008). White dwarfs, which are as common as Sun-like stars, may also provide a source of energy for planets for gigayear (Gyr) durations. White dwarfs have typical masses $0.4-0.9$ $M_\odot$ (Provencal et al. 1998), but have radii only $\approx 1\%$ of the Sun, about the same size as the Earth (Hansen 2004). The most common white dwarfs have surface temperatures of ≈ 5000 K which are referred to as "cool white dwarfs" since hotter white dwarfs are easier to detect (Hansen 2004). Cool white dwarfs typically have luminosities of $10^{-4} L_\odot$, so a planet must orbit at ≈ 0.01 AU to be at a temperature for liquid water to exist on the surface, the so-called habitable zone (Kasting et al. 1993). The small size of white dwarfs can cause large transit depths by Earth-sized or even smaller bodies which could in principle be detectable with ground-based telescopes (Di Stefano et al. 2010; Faedi et al. 2010; Drake et al. 2010).

Prior to becoming a white dwarf, a Sun-like star expands to a red giant, engulfing planets within ≈ 1 AU (e.g., Nordhaus et al. 2010). Planets present in the white dwarf habitable zone (WDHZ) must arrive after this phase. This may occur via several paths (Faedi et al. 2010): planets can form out of gas near the white dwarf, via the interaction or merger of binary stars (Livio et al. 2005), or by capture or migration from larger distances (Debes & Sigurdsson 2002). There are precedents for each of these processes: one neutron star has a planetary system (Wolszczan & Frail 1992) which may have been formed from a disk created after the supernova (Phinney & Hansen 1993); pulsars show low-mass stellar companions being whittled down to planet masses

(Fruchter et al. 1988); and white dwarfs show infrared emission and atmospheric compositions indicative of close orbiting dust and/or bodies (e.g., Zuckerman et al. 2010). Consequently, short period planets around white dwarfs might plausibly exist. I sidestep the question of formation, which has had little theoretical attention, and instead address the location and duration of habitable zones around white dwarfs (Section 2), the detection of planets in the WDHZ, even if their frequency were much less than 1% (Sections 3 and 4), and how characterization of these planets might proceed (Section 5).

2. WHITE DWARF HABITABLE ZONE

I compute the WDHZ boundary following the procedure in Selsis et al. (2007). I determine the white dwarf luminosity and effective temperature, $T_{\rm eff}$, versus age from white dwarf cooling tracks (Bergeron et al. 2001). With the luminosity and effective temperature, I compute the range of distances within which an Earth-like planet could have liquid water on the surface if it were placed there with an intact atmosphere. I use computations of the limits of the habitable zone for stars of different effective temperatures that are based on empirical limits from our solar system combined with one-dimensional radiative—convective atmospheric models for Earth-like planets that include water loss at the inner edge and the maximum CO_2 greenhouse effect at the outer edge (Kasting et al. 1993).

Most white dwarfs have masses $M_{\rm WD} = 0.6 M_\odot$ and CO interior composition, for which I plot the WDHZ versus time in Figure 1 as a blue shaded region. This region shrinks with time as the star cools. A planet enters at the bottom of Figure 1 and moves vertically up the figure as its white dwarf host ages, so it starts off too hot for liquid water, passes through the WDHZ, and then becomes too cold. The duration a planet spends within the WDHZ, $t_{\rm HZ}$, has a maximum of 8 Gyr at ≈ 0.01 AU. Based on the
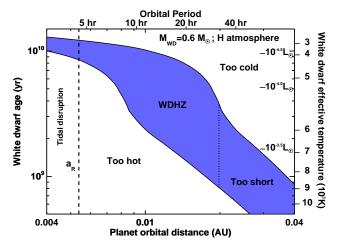
FIG. 1.— WDHZ for $M_{\mathrm{WD}} = 0.6M_\odot$ vs. white dwarf age and planet orbital distance. Blue region denotes the WDHZ. Dashed line is Roche limit for Earth-density planets. Planets to right of dotted line are in the WDHZ for less than 3 Gyr. Planet orbital period is indicated on the top axis; and white dwarf effective temperature on the right axis. Luminosity of the white dwarf at different ages are indicated on right.
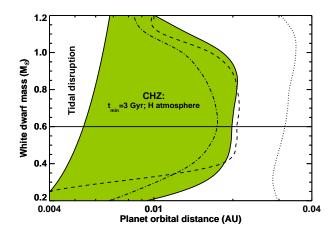

FIG. 2.— CHZ vs. white dwarf mass and planet orbital distance. Green region is the CHZ for $t_{\mathrm{HZ}} > t_{\min} = 3$ Gyr, H-atmosphere. Left solid line is Roche limit for Earth-density planets. The other lines show how the CHZ outer boundary changes for $t_{\min} = 1$ Gyr (dotted line), for $t_{\min} = 5$ Gyr (dash-dotted line), or for an He atmosphere with $t_{\min} = 3$ Gyr (dashed line). Horizontal line indicates the most common white dwarf mass of 0.6 $M_\odot$, plotted in Figure 1.

WDHZ limits, I next define the "continuously habitable zone" (CHZ) as the range of planet orbital distances, a, that are habitable for a minimum duration, $t_{\min}$ (Figure 2). I choose a minimum duration of $t_{\min} = 3$ Gyr, which results in a CHZ within $a < 0.02$ AU: a planet that orbits within this distance spends at least 3 Gyr within the WDHZ. From 0.4 to 0.9 $M_\odot$ with $t_{\min} = 3$ Gyr the outer boundary of the CHZ always falls within 10% of 0.02 AU for hydrogen and helium atmospheres (Figure 2). To check the sensitivity to the white dwarf cooling computations, I have also computed the WDHZ with BASTI models (Salaris et al. 2010), for which I find a slightly longer t_{HZ}. I have also computed the CHZ for atmospheres with $t_{\min} = 1$ Gyr and 5 Gyr which shifts the outer boundary of the CHZ outward/inward by a factor of $\approx 1.5/0.7$ (Figure 2).

There are several important consequences of the WDHZ and CHZ. First, the range of white dwarf temperatures in the portion of the CHZ within the WDHZ is that of cool white dwarfs, ≈ 3000–9000 K (right hand axis in Figure 1), similar to the Sun. At the hotter end higher ultraviolet flux might affect the retention of an atmosphere, these planets would need to form a secondary atmosphere, as occurred on Earth. Excluding higher temperature white dwarfs only slightly modifies the CHZ since they spend little time at high temperature. Cool white dwarfs are photometrically stable (Fontaine & Brassard 2008), which is critical for finding planets around them. Second, for white dwarfs with temperatures $\gtrsim 4500$ K, the WDHZ is exterior to the Roche limit (tidal disruption radius), $a_{\mathrm{R}} = 0.0054 \mathrm{AU} (\rho_{\mathrm{p}}/\rho_\oplus)^{-1/3} (M_{\mathrm{WD}}/0.6M_\odot)^{1/3}$, where $\rho_{\mathrm{p},\oplus}$ are the mass densities of the planet and of Earth. Consequently, the 3 Gyr CHZ lies between $a_{\mathrm{R}} < a < 0.02$ AU, indicated with the green region in Figure 2.

Third, the CHZ occurs at white dwarf luminosities of $10^{-4.5}$ to $10^{-3} L_\odot$, about 10 magnitudes fainter than the Sun, which sets the minimum telescope size for detection. Finally, the orbital period of white dwarfs in the CHZ is ≈ 4–32 hr. At this period the timescales for tidal circularization and tidal locking are ≈ 10–1000 years, so rocky planets will be synchronized and circularized (Heller et al. 2011); the side of the planet near the star will have a permanent day, while the far side will have a permanent night. The planet will orbit stably as it cannot raise a tide on the compact white dwarf. Radiation drag will not cause the orbit to decay, but magnetic field drag might, depending on the planet's conductivity (Li et al. 1998).

3. DETECTION OF PLANETS IN THE WHITE DWARF HABITABLE ZONE

I plot example light curves of planets in the WDHZ in Figure 3 for sizes within a factor of ≈ 2 of Earth orbiting a white dwarf near the peak of the white dwarf luminosity function. The transits last ≈ 2 minutes, and have a maximum depth of 10%—100%; these events can be detected at a 100 pc distance with a 1 m ground-based telescope. To detect planets in the CHZ one must monitor a sample of white dwarfs for the duration of the orbital period at 0.02 AU, and planets present in edge-on orbits will be seen to transit their host stars. The transit probability is

$$p_{\mathrm{trans}} = 1.0\% \left(\frac{R_{\mathrm{p}}/R_\oplus + R_{\mathrm{WD}}/0.013R_\odot}{a/0.01\mathrm{AU}} \right), \quad (1)$$

so for every 100 Earths orbiting white dwarfs at 0.01 AU with random orientations, on average one will be seen to transit.

I define $\eta_\oplus$ to be the number of planets with $0.1 M_\oplus < M_{\mathrm{p}} < 10 M_\oplus$ in the 3 Gyr CHZ ($a < 0.02$ AU). To measure $\eta_\oplus$ to an accuracy of $\approx 33\%$ requires detecting ≈ 9 planets, so one must survey $\approx 10^3 \eta_\oplus^{-1}$ white dwarfs.

4. SURVEY STRATEGY

The local density of white dwarfs is $(4.7 \pm 0.5) \times 10^{-3}$ pc^{-3} (Harris et al. 2006). For a survey out to $D_{\max} < 200$ pc, the white dwarfs should be nearly isotropically spaced on the sky at one per $\approx 2(100\mathrm{pc}/D_{\max})^3$ deg^2. This exceeds the field of view of most telescopes, so each

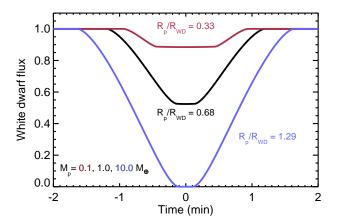FIG. 3.— Example light curves of habitable Earth-like planets transiting a $0.6 M_\odot$ white dwarf ($T_{\rm eff} = 5200$K, $R_{\rm WD} = 0.013 R_\odot$, inclination = $89°.9$, 10% linear limb darkening, and $a = 0.013$ AU) with masses of $0.1 M_\oplus$ (red, about Mars mass), $1.0 M_\oplus$ (black, Earth twin), and $10.0 M_\oplus$ (blue, super-Earth). The ratios of the planet radii, $R_{\rm p}$, to white dwarf radius, $R_{\rm WD}$, are indicated.

white dwarf must be separately surveyed for the presence of transiting planets.

I have simulated an all-sky survey with a worldwide network of 1 m aperture telescopes to monitor the white dwarf CHZ (typically 32 hr, during which telescopes distributed in longitude follow a single star) following Nutzman & Charbonneau (2008) to compute the telescope sensitivity, including sky and read noise, and assuming an exposure time of 15 s; I conservatively expanded the error bars an additional 50%. Each white dwarf is given a multi-planet system whose innermost planet is chosen from a log-normal centered at $2a_{\rm R}$ with width of 0.5 dex, with subsequent planets packed as closely as allowed by dynamical stability on a timescale of 10^9 yr (Zhou et al. 2007), leading to a uniform distribution in $\log a$, with a gradual cutoff within $2a_{\rm R}$. The planet masses are drawn from $dn/dM_{\rm p} \propto M_{\rm p}^{-\alpha}$ from $10^{-2} M_\oplus$ ($\approx$Moon) to $10^2 M_\oplus$ ($\approx$Saturn), with $\alpha = 4/3$ to match the observed slope measured with the *Kepler* satellite (Borucki et al. 2011), as well as that found in the solar system. I assumed Earth-composition planets with the radius determined from the mass according to Seager et al. (2007). Two exposures within transit with a signal-to-noise of at least 6 constitute a detection; this keeps the false-positive level to <1% for the entire survey. I then scale the simulated detection rates with $\eta_\oplus$ to determine the expected number of detected planets.

To detect 9 ± 3 planets, for $\eta_\oplus = 50\%$ a survey of 2800 white dwarfs within 52 pc is required for a total on-sky time of 10 years (for a single telescope with 31 hours per white dwarf on average). A smaller planet frequency of $\eta_\oplus = 10\%$ requires $\approx$20,000 white dwarfs within 100 pc for a total 69 years of telescope time on sky. For a network of twenty 1 m telescopes distributed around the globe, such as the Las Cumbres Observatory Global Telescope (LCOGT; Hidas et al. 2008), or the Whole Earth Telescope (WET Nather et al. 1990), devoted to observing white dwarfs at 25% efficiency (50% of time at night, 50% weather loss), the total calendar time required would be 2 years for a survey of 2800 white dwarfs and 14 years for a survey of 20,000. If the CHZ is surveyed to only

0.01 AU, this would decrease the required calendar time to 8.5 months and 5 years, respectively, but would also decrease the planet yield.

Figure 4 shows the probability distribution for planets detected in 10^4 survey simulations. Each one surveys 20,000 single white dwarfs out to 100 pc for planets within 0.02 AU. Of the detected planets, an average of 40% will be currently within the WDHZ. Remarkably, the detection probability peaks near planets of the size and temperature of Earth due to the coincidence in size of the Earth and white dwarfs, and the coincidence between the WDHZ at the peak of the white dwarf luminosity function and $2a_{\rm R}$. This leads to the following biases: (1) large planets have a higher transit detection probability $\propto R_{\rm p} dn/dR_{\rm p}$, so the number detected declines if $dn/dR_{\rm p}$ is steeper than $R_{\rm p}^{-1}$; (2) small planets cause shallower transits for $R_{\rm p} \ll R_{\rm WD} \approx R_\oplus$, so the detection rate scales as $\propto R_{\rm p}^6 dn/dR_{\rm p}$ (Pepper et al. 2003), although the range of luminosities of white dwarfs flattens this decline; (3) cooler planets have a smaller probability of transit, so fewer are detected as $\propto T_{\rm p}^4$ for small $T_{\rm p}$ and a uniform distribution in $\log a$; and (4) hotter planets orbit hotter stars, which are less numerous, $dn/dT_{\rm WD} \propto T_{\rm WD}^{-3.9}$ for large $T_{\rm WD}$ (Hansen 2004). Although these trends should occur for any volume-limited survey, the break in the radius detection limit depends on the size of the telescope and signal-to-noise cutoff that is chosen: larger telescopes or smaller signal-to-noise cuts will be more sensitive to small radius planets. Figure 4 is sensitive to the properties of the planet population: if the inner cutoff, $a_{\rm in}$, is further/closer, then the peak temperature moves to cooler/hotter temperatures, $\propto a_{\rm in}^{-1/2}$, and the total number of planets detected declines/increases as $a_{\rm in}^{-1}$ due to the lower/higher transit probability. If the planet size distribution is steeper/flatter, then the detected planet distribution peaks at smaller/larger sizes.

Prior to such a survey, a nearby sample of cool white dwarfs must be found using measurements of the reduced proper motion. Ongoing and planned deep astrometric surveys, such as 90 Prime, Skymapper, Pan-STARRS, URAT, and GAIA, should find most cool white dwarfs out to 100 pc ($V<21$) within the decade (Henry et al. 2009; Kalirai et al. 2009). Some of these surveys might also find transits if the requirement of three epochs in transit is relaxed. For example, GAIA will observe 200,000 disk white dwarfs 50-100 times each (Perryman et al. 2001), possibly detecting one epoch in eclipse for $\approx$10% of these stars with habitable transiting planets.

For values of $\eta_\oplus < 10\%$, more stars must be observed to detect planets, so a better strategy is to observe multiple white dwarfs simultaneously with a wide-field imager with fast readout, such as the Large Synoptic Survey Telescope (LSST LSST Science Book 2009). The LSST survey is expected to detect $\approx 10^7$ white dwarfs over half of the sky at $>5\sigma$ to $r<24.5$ with $\approx$1000 epochs each and two 15 s exposures per epoch over the duration of the 10 year survey. Since LSST is a magnitude-limited survey, the white dwarf temperature distribution peaks at 10^4K. I have taken the simulated detected distribution of white dwarfs for LSST (Jurić et al. 2008), created simulated light curves for white dwarfs with planets, and
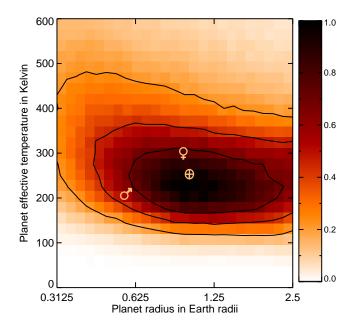
FIG. 4.— Probability density, $d^2n/(dT_\mathrm{p}d\log R_\mathrm{p})$, of detected planets vs. planet radius, R_p (log axis scale), and planet effective temperature, T_p (assuming the same albedo as Earth). The contours enclose 25%, 50%, and 75% of all detected planets; the contour levels are 29%, 53%, and 76% of the peak density. Earth ($\oplus$), Mars ($\male$), and Venus ($\female$) symbols indicate the radii and effective temperatures of these solar system planets.

added noise (LSST Science Book 2009). I find LSST can detect >9 CHZ planets if $\eta_\oplus > 5 \times 10^{-3}$, where detection requires that at least three epochs fall within transit with two points each detected at $>7\sigma$. The LSST survey will be biased toward detecting shorter period ($\propto P^{-4/3}$) and large-size planets that have yet to enter the WDHZ since their stars are hotter. This could be improved by either continuously observing some fields for several nights, or taking more exposures per field, resulting in detection of smaller, cooler planets, thus constraining smaller $\eta_\oplus$. LSST will identify the white dwarfs with reduced proper motion measurements as the survey is being carried out.

I estimate that $>10^3$ double white dwarf eclipsing binaries with orbital periods similar to WDHZ planets will be found with LSST using the BSE population synthesis model for binary stars (Hurley et al. 2002) with parameters taken from observed binaries (Raghavan et al. 2010). I find that about 2.5% of white dwarfs will have a white dwarf companion with a period in the range of 8—64 hr which might be mistaken for a transiting CHZ planet if these are viewed edge-on. Follow-up of planet candidates will be required to distinguish the two possibilities: white dwarf binaries will show primary and secondary eclipses of different depths (if the two white dwarfs differ in temperature), offset secondary eclipses due to light travel time, gravitational lensing (Agol 2002), and Doppler modulation, and an eclipse shape that differs from planetary transits if non-grazing. I simulated light curves of white dwarf binaries including these effects and find that in the worst case of two white dwarfs with identical temperatures these distinguishing features may be detected with 10—100 m ground-based telescopes for systems out to 50—100 pc, either photometrically or with radial velocities. Another concern is grazing eclipses from white

dwarf/M dwarf binaries; these can be identified by the eclipse shapes, spectral energy distribution, and differing secondary eclipse depths.

5. PLANET CHARACTERIZATION

The parallax and spectrum of a white dwarf yield its mass, luminosity, atmospheric composition, and radius; then the transit depth gives the planet radius. The planet's mass cannot be measured from Doppler shifts due to the featureless spectra of cool white dwarfs, but may be bracketed by the range of compositions for planets of a given size (Seager et al. 2007). The mass might be measured by observing wavelength dependent absorption, such as Rayleigh scattering that varies as $8H/R_\mathrm{p}\ln\lambda$ (Lecavelier Des Etangs et al. 2008), where H is the atmospheric scale height, causing the transit depth to vary by ≈few millimagnitude over 400—500 nm if Rayleigh scattering dominates over other sources of opacity. If atmospheric molecular weight can be estimated, so can the planet mass (Miller-Ricci et al. 2009). If two planets transit a white dwarf (about 2.5% of the time for mutual inclinations within $5°$ and in a packed planet system), then transit timing variations might constrain the planet masses if the orbital period ratio is nearly commensurate (Holman & Murray 2005; Agol et al. 2005). Infrared phase variation of planets (Knutson et al. 2007) in the CHZ is ≈0.5%—2% at 15—20 μm; however, I estimate that the *James Webb Space Telescope* (*JWST*) cannot detect this for cool white dwarfs due to telescope noise. For a hotter white dwarf of 10^4 K at 100 pc with an Earth-like planet at 0.01 AU with a day—night contrast of 30%, the phase variation of 0.1% at 7.7 μm might be detectable at 9σ with the MIRI imager on *JWST* (Swinyard et al. 2004).

Several topics require further study. The global climate models for determining the WDHZ should include fast synchronous rotation, magnetic fields, varied planet atmospheric composition, radiogenic heating, and white dwarf cooling. The WDHZ is a necessary but insufficient criteria for habitability. For example, planets that start hot may not retain their atmospheres, as has also been argued for planets orbiting M dwarfs (Lissauer 2007); this may require volatile delivery from more distant bodies in the system (Jura & Xu 2010) or planetary outgassing. To retain an atmosphere might require a larger planet escape velocity, possibly favoring super-Earths for habitability.

Formation mechanisms must be modeled to help motivate future surveys. For example, gravitational interactions of a planet and star with a third companion body may be responsible for creating hot Jupiters (Fabrycky & Tremaine 2007), which is also promising for moving distant planets around white dwarfs to $2a_\mathrm{R} \approx 0.01$ AU, the tidal circularization radius (Ford & Rasio 2006). It is also possible that tidal disruption of a planet or a companion star will result in the formation of a disk which may cool and form planets (Guillochon et al. 2010), out of which a second generation of planets might form (Menou et al. 2001; Perets 2010; Hansen et al. 2009).

The most common white dwarf has $T_\mathrm{eff} \approx 5000$ K, close to that of the Sun; consequently, inhabitants of a planet in the CHZ will see their star as a similar angular size and color as we see our Sun. The orbital and spin pe-

riod of planets in the CHZ are similar to a day, causing Coriolis and thermal forces similar to Earth. The night sides of these planets will be warmed by advection of heat from their day sides if a cold-trap is avoided (Merlis & Schneider 2010). Transit probabilities of habitable planets are similar for cool white dwarfs and Sun-like stars, but the white dwarf planets can be found using ground-based telescopes (e.g., LCOGT, WET, and LSST) at a much less expensive price than space-based planet-survey telescopes.

Note added in proof. René Heller informed me that Monteiro (2010) discussed the white dwarf habitable zone for known white dwarf stars, showing a boundary similar to that in Figure 1.

REFERENCES

Agol, E. 2002, ApJ, 579, 430
Agol, E., Steffen, J., Sari, R., & Clarkson, W. 2005, MNRAS, 359, 567
Bergeron, P., Leggett, S. K., & Ruiz, M. T. 2001, ApJS, 133, 413
Borucki, W. J., et al., 2011, ApJ, 728, 117
Debes, J. H., & Sigurdsson, S. 2002, ApJ, 572, 556
Di Stefano, R., Howell, S. B., & Kawaler, S. D. 2010, ApJ, 712, 142
Drake, A. J., et al. 2010, arXiv:1009.3048
Fabrycky, D., & Tremaine, S. 2007, ApJ, 669, 1298
Faedi, F., West, R. G., Burleigh, M. R., Goad, M. R., & Hebb, L. 2010, MNRAS, 410, 899
Fontaine, G., & Brassard, P. 2008, PASP, 120, 1043
Ford, E. B., & Rasio, F. A. 2006, ApJ, 638, L45
Fruchter, A. S., Stinebring, D. R., & Taylor, J. H. 1988, Nature, 333, 237
Guillochon, J., Ramirez-Ruiz, E., & Lin, D. N. C. 2010, arXiv:1012.2382
Hansen, B. 2004, Phys. Rep., 399, 1
Hansen, B. M. S., Shih, H., & Currie, T. 2009, ApJ, 691, 382
Harris, H. C., et al. 2006, AJ, 131, 571
Heller, R., Leconte, J., & Barnes, R. 2011, A&A, 528, 27
Henry, T. J., Monet, D. G., Shankland, P. D., Reid, M. J., van Altena, W., & Zacharias, N. 2009, Astro2010: The Astronomy and Astrophysics Decadal Survey, 123 (arXiv:0902.3683)
Hidas, M. G., Hawkins, E., Walker, Z., Brown, T. M., & Rosing, W. E. 2008, Astronomische Nachrichten, 329, 269
Holman, M. J., & Murray, N. W., 2005, Science, 307, 1288
Hurley, J. R., Tout, C. A., & Pols, O. R. 2002, MNRAS, 329, 897
Jura, M., & Xu, S. 2010, AJ, 140, 1129
Jurić, M., et al. 2008, ApJ, 673, 864
Kalirai, J., et al. 2009, Astro2010: The Astronomy and Astrophysics Decadal Survey, 147
Kasting, J. F., Whitmire, D. P., & Reynolds, R. T. 1993, Icarus, 101, 108
Knutson, H. A., et al. 2007, Nature, 447, 183
Lecavelier Des Etangs, A., Pont, F., Vidal-Madjar, A., & Sing, D. 2008, A&A, 481, L83
Li, J., Ferrario, L., & Wickramasinghe, D. 1998, ApJ, 503, L151
Lissauer, J. J. 2007, ApJ, 660, L149
Livio, M., Pringle, J. E., & Wood, K. 2005, ApJ, 632, L37

LSST Science Collaborations & LSST Project 2009, LSST Science Book, Version 2.0, arXiv:0912.0201 (http://www.lsst.org/lsst/scibook)
Lunine, J. I., et al. 2008, Astrobiology, 8, 875
Menou, K., Perna, R., & Hernquist, L. 2001, ApJ, 559, 1032
Merlis, T. M., & Schneider, T. 2010, J. Adv. Model. Earth Syst., 2, 13
Miller-Ricci, E., Seager, S., & Sasselov, D. 2009, ApJ, 690, 1056
Monteiro, H., 2010, Bol. Soc. Astron. Brasileira, 29, 22
Nather, R. E., Winget, D. E., Clemens, J. C., Hansen, C. J., & Hine, B. P. 1990, ApJ, 361, 309
Nordhaus, J., Spiegel, D. S., Ibgui, L., Goodman, J., & Burrows, A. 2010, MNRAS, 408, 631
Nutzman, P., & Charbonneau, D. 2008, PASP, 120, 317
Pepper, J., Gould, A., & Depoy, D. L. 2003, Acta Astronomica, 53, 213
Perets, H. B. 2010, arXiv:1012.0572
Perryman, M. A. C., de Boer, K. S., Gilmore, G., Høg, E., Lattanzi, M. G., Lindegren, L., Luri, X., Mignard, F., Pace, O., & de Zeeuw, P. T. 2001, A&A, 369, 339
Phinney, E. S., & Hansen, B. M. S. 1993, in ASP Conf. Ser. 36, Planets Around Pulsars, ed. J. A. Phillips, S. E. Thorsett, & S. R. Kulkarni (San Francisco, CA: ASP), 371
Provencal, J. L., Shipman, H. L., Høg, E., & Thejll, P. 1998, ApJ, 494, 759
Raghavan, D., et al. 2010, ApJS, 190, 1
Salaris, M., Cassisi, S., Pietrinferni, A., Kowalski, P. M., & Isern, J. 2010, ApJ, 716, 1241
Seager, S., Kuchner, M., Hier-Majumder, C. A., & Militzer, B. 2007, ApJ, 669, 1279
Selsis, F., Kasting, J. F., Levrard, B., Paillet, J., Ribas, I., & Delfosse, X. 2007, A&A, 476, 1373
Swinyard, B. M., Rieke, G. H., Ressler, M., Glasse, A., Wright, G. S., Ferlet, M., & Wells, M. 2004, Proc. SPIE, 5487, 785
Wolszczan, A., & Frail, D. A. 1992, Nature, 355, 145
Zhou, J., Lin, D. N. C., & Sun, Y. 2007, ApJ, 666, 423
Zuckerman, B., Melis, C., Klein, B., Koester, D., & Jura, M. 2010, ApJ, 722, 725