Finding habitable earths around white dwarfs with a robotic telescope transit survey

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ABSTRACT

I discuss the possibility that white dwarfs might harbor habitable planets at 0.01 AU that arrive there after the red giant phase. These planets would be detectable with ground-based telescopes via deep transits of the star, and a transit survey of the nearest white dwarfs would favor detection of Earth-temperature planets, assuming they could form as close as twice the Roche limit. I show that a robotic survey is required for habitable planet transit detection around white dwarfs due to the large amount of sky coverage, geographical coverage with multiple telescopes, and significant observing time involved. Robotic telescopes such as LCOGT, ATLAS/WIST, and LSST could place interesting limits on the frequency of planets in the 3 Gyr continuously habitable zone of white dwarfs, possibly constraining frequencies as small as 0.1%.

Keywords: Extrasolar planets, white dwarfs, habitable zone, transit survey

1. INTRODUCTION

The search for planets similar to the Earth is one of the prime motivations for the study of extrasolar planets: we would like to find out how rare or common our Earth is, and we would like to know whether life exists in other solar systems. In designing this search, astronomers have primarily focused their efforts on nuclear burning main sequence stars as these have a steady, long-lived source of energy to maintain a slowly-varying temperature on the planet's surface, a prerequisite for stable chemistry. However, there is another extended phase of a star's life during which its luminosity is nearly constant: that of a white dwarf. Figure 1a shows the luminosity of a star slightly more massive than our Sun versus time: a comparable amount of time is spent in the main sequence phase as the white dwarf phase, and the rate of change of luminosity is gradual for billions of years in both phases. The model up until the white dwarf stage is taken from[1*], while the white dwarf cooling track is taken from[2†].

Now, the problem with finding habitable planets around a white dwarf is that the star is so underluminous that the planet must be quite close to receive the same flux as the Earth receives from the Sun. Figure 1b shows the planet orbital distance at which it receives a flux $S_0 = 1360$ W m^{-2} (the Solar constant) as a dashed line; for white dwarfs the habitable zone is $\approx 10^2$ times closer than on the main sequence. The solid line in that figure shows the size of that star versus time, and during the red giant phase the white dwarf habitable zone (WDHZ) will be engulfed by the star, leaving no planets after this phase.

However, it may be possible that planets could arrive in the WDHZ after the red giant phase, either by reforming close to the white dwarf or migrating inwards from larger distances (see §4). Even if theorists could estimate the frequency of short-period planets around white dwarfs, it will require an astronomical survey to determine the true frequency as any model will be plagued with uncertainty. Two historical lessons indicate this: pulsar planets and hot jupiters. Pulsars were not expected to host multi-planet systems due to being preceded by a supernova explosion, yet the first exoplanets were found to orbit a pulsar.[3] Theorists have pieced together ideas for how these may have formed out of a disk of gas after the supernova; however, these theories have been difficult to test due to the lack of discovery of planets about other pulsars, possibly due to timing noise. Just as no one expected a multi-planet system to orbit a pulsar, short-period "hot" jupiters were predicted to not exist orbiting sun-like stars.[4] But, beginning with 51 Pegasi B,[5] copious numbers have been found in the last decade. Most theorists have not given up on the core-accretion model, and appeal to migration of these planets inwards

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*SPectral Evolution from EDinburgh-Penn, SPEED, http://icc.ub.edu/ jimenez/SPEED/

†http://www.fcaglp.unlp.edu.ar/evolgroup/tracks.html

after their formation[6] to explain the hot jupiter population which orbit about 1% of main-sequence stars.[7] These two examples indicate that we should not base our knowledge upon the expectations of astrophysical theory; we need to see whether short period planets exist around white dwarfs.

This paper follows the arguments presented in,[8] but provides a different presentation and complementary material.

2. WHITE DWARF COOLING

The Mestel cooling law for white dwarfs in which $L \propto t^{-7/5}$ approximates white dwarf cooling fairly well (this is somewhat coincidental; the actual physics that determines the cooling is much more complex than the ingredients of Mestel cooling). The distribution of white dwarf temperatures peaks just shortward of the temperature of the Sun, $T_\odot$. This is due to the coincidence that cooling times of solar temperature white dwarfs are similar to the age of the galaxy. This can be seen with a simple toy model as follows. Above a luminosity of $10^{-4}L_\odot$, white dwarfs cool at a rate

$$L = 2 \times 10^{-3} L_\odot \left(\frac{M_{WD}}{M_\odot} \right) \left(\frac{t_{WD}}{1\mathrm{Gyr}} \right)^{-7/5}. \tag{1}$$

Assume that stars are born in the Milky Way disk at a constant rate for a time t_{disk} with a Salpeter mass function $(dn/dM_i \propto M_i^{-\alpha})$, where M_i is the initial mass of the white-dwarf progenitor in solar masses. If the main-sequence lifetime is given by $t_{MS} = 10\mathrm{Gyr} M_i^{-\beta}$ and if one assumes that all white dwarfs have a mass of $0.6M_\odot$, then one can show that the temperature distribution of white dwarfs is given approximately by

$$\frac{dn}{dT_{WD}} \propto \left(1 - x^{-20/7} \right)^{\frac{\alpha-1}{\beta}} x^{-27/7}, \tag{2}$$

where $x = (T_{WD}/T_\odot)(t_{disk}/t_C)^{7/20}$ and t_C is the cooling time of a white dwarf with the temperature of the Sun. For a $0.6M_\odot$ white dwarf, equation 1 implies $t_C = 4.2$ Gyr. Now, this temperature distribution has a maximum at $x = 1.106$ for $\alpha = 2.35$ and $\beta = 3$, which means the white dwarf temperature distribution peaks at $T_{WD}^{peak} = 1.106T_\odot(t_C/t_{disk})^{7/20} = 0.847T_\odot = 5000$ K for $t_{disk} = 9$ Gyr. *Consequently the peak temperature of disk white dwarfs is similar to the temperature of the Sun.* At this temperature the cooling time is $t_{WD} = (0.847)^{-20/7}t_C = 6.75$ Gyr. Thus cool white dwarfs will shine for a biologically interesting timescale, providing a stable source of energy for planets within their habitable zones.

3. WHITE DWARF HABITABLE ZONE

There are significant deviations from the Mestel cooling law due to a range of physical effects, most importantly for cool white dwarfs are crystallization and gravitational separation. So instead of equation 1, I used the cooling models computed by Bergeron et al.[9] to compute the white dwarf luminosity as a function of time since becoming a white dwarf (these were used rather than more recent models simply because they were available for a wide range of white dwarf mass). I have computed the white dwarf habitable zone using the maximum habitable zone boundaries given in Kasting et al. (1993) as a function of the effective temperature of the star, which roughly correspond to the fluxes received by Venus at the inner edge and Mars at the outer edge. The flux ratio S_{eff} at the boundaries is solely a function of effective temperature which I interpolated quadratically given the three values reported in.[10] The boundaries of the habitable zone are then $a_{HZ} = \sqrt{L_{WD}/S_{eff}}$, where a_{HZ} is the semi-major axis in AU and L_{WD} is the white dwarf luminosity in units of the Solar luminosity, $L_\odot$. This likely brackets the possible range of distances at which a planet may have liquid water at the surface assuming the maximum CO_2 greenhouse effect at the outer edge and water loss at the inner edge. The Kasting et al. models do not take into account tidal locking of the planet, which might significantly alter the habitable zone, and does not take into account atmospheric loss for hotter stars (I extrapolated the models of Kasting beyond the maximum temperature of 7600 K for which they were computed for). Due to the decline of white dwarf luminosity with time, the habitable zone shrinks as the star cools. For a planet at semi-major axis a, I have also computed the duration of time that a planet at a particular orbital radius would spend within the WDHZ. For white dwarfs at the peak of the luminosity function which have $T_{eff} \approx 5000$ K, the WDHZ is centered around
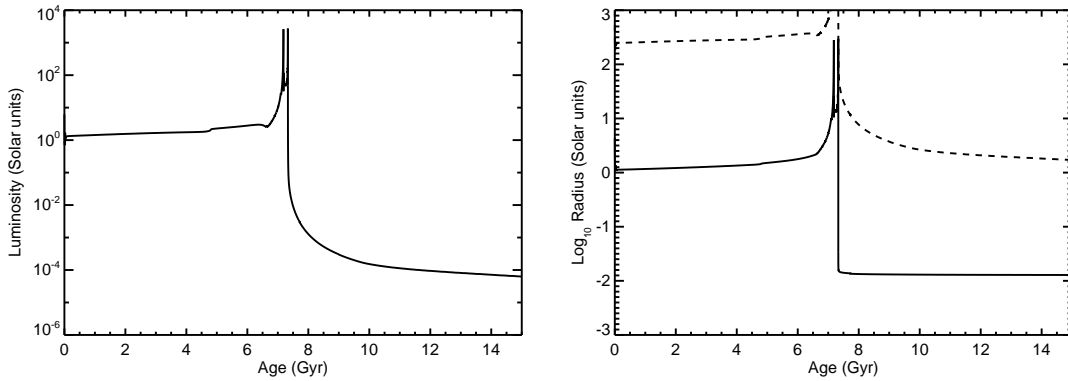
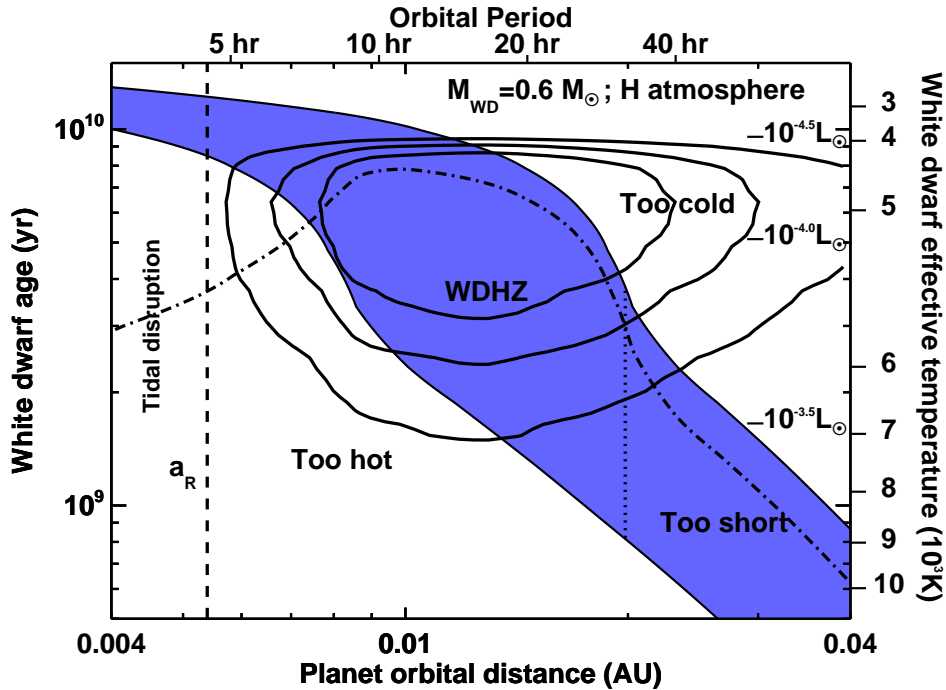Figure 1. Luminosity (left) and radius (right) of an $M = 1.2 M_\odot$ versus time.

Figure 2. WDHZ (blue shaded region) versus white dwarf age and planet semi-major axis. Vertical dashed line is Roche limit, a_R; dash-dot line is duration within the WDHZ; vertical dotted line is 3 Gyr CHZ boundary. Top axis indicates orbital period; right axis indicates the white dwarf effective temperature. Tick marks on right indicate the luminosity of the white dwarf. Contours contain 25%, 50%, and 75% of white dwarfs which have transiting planets for the model described in the text.

≈ 0.01 AU, which is also the location where planets spend the longest duration in the WDHZ, about 8 Gyr (this is not a coincidence since the white dwarf luminosity function peaks where the cooling time is longest). A surprising coincidence is that this distance is nearly twice that of the Roche limit; there is no physical law that dictates these two quantities should be comparable. Twice the Roche limit is the distance at which planets should tidally circularize, and it also seems to be the closest distance at which planets orbit main sequence stars. This also leads to the definition of the continuously habitable zone (CHZ): the range of distances from a white dwarf at which a planet will spend at least 3 Gyr within the WDHZ. I find that for white dwarfs in the mass range from 0.4 - 0.9 $M_\odot$ the CHZ is within 0.02 AU (Agol 2011).

The near coincidence between the Roche limit and WDHZ (at the peak of the luminosity function) has an

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important impact on the detectability of these planets: a transit survey of nearby white dwarfs should be *biased* towards detecting planets in or near the WDHZ. If they are distributed at a range of orbital separations, a, down to $a > a_{in} \approx 2a_R$, then the closest planets have the highest probability of transit, $p_t \propto a^{-1}$, so the planets in the WDHZ will be the most probable planets to detect. Of course the transit detection probability needs to be folded with planet frequency as a function of a, to obtain the detected planet distribution, and Figure 2 shows that if planets are distribution uniformly in $\log a$ down to $2a_R$, the transiting planet population peaks at the WDHZ. Figure 2 also shows that the temperature distribution peaks near 5000 K; overplotted are contours of the distribution of planets in a model in which stars are formed continuously over 12 Gyr using the SSE model[11] with white dwarf cooling computed from Bergeron[9] and the planets are drawn from a uniform distribution in $\log a$ with a gradual cutoff within $2a_R$.

The second coincidence is that Earth-sized planets are similar in size to white dwarf stars. This causes deep transits: an Earth-sized planet cause a 50% dip lasting ≈ 2 minutes if it orbits a 0.6 $M_\odot$ CO white dwarf. This depth is easily detected with ground-based telescopes; the faintness of white dwarfs, though, sets the minimum telescope size for detection out to 100 pc at about 1 meter. This has another consequence that a volume-limited survey can be biased towards detection of Earth-sized planets if the number of planets decreases steeply enough with size and if the survey detection limit is such that Earths can be detected for the most distant stars in a volume-limited survey.

The third coincidence is that the rotational period in the WDHZ at the peak of the luminosity function is about 1 day (Figure 2). This means that: (1) transit surveys simply need to monitor a white dwarf for $\approx$ day to determine if a planet transits the star; (2) the Coriolis and centrifugal forces on these planets will be similar to those on Earth. This also sets the minimum duration of observation to detect a transit of a planet orbiting a white dwarf edge-on.

4. FORMATION OF TERRESTRIAL PLANETS IN WHITE DWARF HABITABLE ZONES

Potentially multiple paths exist for formation of terrestrial planets around white dwarfs, although the branching ratios for these paths have yet to be computed. Several paths bear similarity to the paths to formation of pulsar planets[12] since both neutron stars and white dwarfs are stellar remnants. The major difference between the formation of neutron stars and white dwarfs is that the former happens rapidly in a dynamical time, while the latter happens gradually over thousands of years. Here are some possible paths of formation of short period planets around white dwarfs:

- Accretion from a companion star which leaves behind a planet-mass core just outside the Roche radius;

- Merger of two white dwarfs, resulting in a disk surrounding the merger remnant out of which planets form;[13]

- If the white dwarf progenitor has a planetary system at large enough semi-major axis to survive the asymptotic-giant phase and has a companion star, the mass loss of the progenitor will modify the orbital elements of the binary, possibly resulting in instability of the planetary system, in some cases leading to a planet to be scattered inward. Alternatively a Kozai resonance might pump the eccentricity of a planet causing its pericenter to approach the Roche radius;

- If the star has an asymmetric wind during the mass-loss phase it can receive a kick[14] which in some cases might cause the resulting white dwarf to collide with a binary companion, leading to accretion of gas and the formation of a disk;

- Secular dynamical instabilities can pump the eccentricities of multi-planet systems that survive the red-giant phase, a process that may continuously create short-period planets.[15, 16] These planets may then be tidally disrupted[17] or tidally circularized.[18]

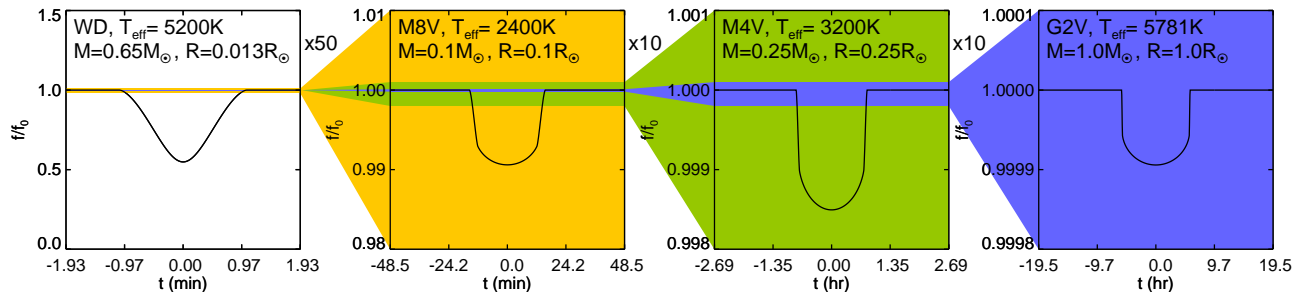- If tidally disrupted, a second generation of planets may form close to the star.[19]

Figure 3. Comparison of the transits of a habitable Earth-sized planet orbiting main-sequence dwarfs stars of three varieties as well as a white dwarf star at the peak of the luminosity function. The succeeding panels expand the vertical axis by factors of 50, 10 and 10; the change in axis range causes the colored regions to change between the four panels.

There are indications that such processes might occur around white dwarfs: some white dwarfs show evidence for metal pollution in their atmospheres and infrared emission due to orbiting dust,[20–22] albeit the current data only place a small lower limit on the mass of material. Since the white dwarf star starts off hot, the planets may lose their atmospheres if they form or migrate inwards too early around after the red giant phase; alternatively a dry planet may reform an atmosphere if enough volatiles are delivered or via outgassing.

5. TRANSIT DETECTION AROUND WHITE DWARFS

The great advantage of searching for planets in the habitable zones of white dwarfs is their small size relative to Earth. Table 1 gives a comparison of the properties of main sequence stars of various spectral types with a white dwarf. Although the transit is much deeper for a white dwarf than for any main sequence stars (Figure 3), the transit lasts a much shorter time. The deepness of the transit wins out, however, when observing from the ground since atmospheric fluctuations and correlated noise cause shallow transits to be nearly undetectable; the best data obtained from the ground is only sensitive to $\approx$ mmag transit depths, so only late M dwarfs or white dwarf stars can have ground-detectable Earth-sized planet transits. In fact, the M dwarf advantage has already been realized by David Charbonneau's *Mearth* survey which employs transit observations with a group of robotic telescopes, and has found a super-Earth planet that transits a nearby low-mass star, GJ 1214b.[23] However, this planet has a volume about 20 times that of Earth, is too hot to be habitable, and it also likely has a very thick atmosphere.

Table 1. T, M_*, R_*: stellar effective temperature, mass and radius; a_{HZ}: semi-major axis in the habitable zone; p_{HZ}: probability of transit in the habitable zone; n: number density; $(R_\oplus/R_*)^2$: transit depth neglecting limb-darkening; L: stellar luminosity; P_{HZ}: period of orbit at center of habitable zone; T_{trans}: duration of transit for a habitable planet in an edge-on orbit.

Type	T (K)	M_* ($M_\odot$)	R_* ($R_\odot$)	a_{HZ} (AU)	p_{HZ}	n (pc^{-3})	$(R_\oplus/R_*)^2$	L ($L_\odot$)	P_{HZ}	T_{Trans} ($b=0$)
G2V (Sun)	5781	1.	1.	1	0.47%	6×10^{-3}	0.0084%	1	1yr	13 hr
M4V	3200	.25	.25	.077	1.58%	3×10^{-2}	0.13%	6×10^{-3}	15.6 d	1.8 hr
M8V	2400	.10	.10	.017	2.97%	3×10^{-2}	0.84%	3×10^{-4}	2.56 d	0.5 hr
DC WD	5200	.65	.013	.010	0.98%	5×10^{-3}	48.8%	1×10^{-4}	12 hr	2.3 min

Stellar variability is another limitation for transit detection, and convection and star spots on main sequence stars may limit the precision of transit detection. This can take two forms: overall variability of the brightness of the star which causes correlated noise variations which limit the detection of the dip due to a transit, or crossing of a planet over regions of the star with varying surface brightness, such as star spots. For white dwarf stars above a temperature of about 11,000 K there are atmospheric instabilities which cause variation in brightness; this limits the possibility of transit detection for these stars. However, cooler white dwarfs are expected to be photometrically stable, and thus transit detection should not be limited by stellar variability.

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To probe the CHZ requires observing for $P = 32\text{hr}(a/0.02\text{AU})^{3/2}(M_{WD}/0.6M_\odot)^{-1/2}$, the period of a planet's orbit at the outer edge of the habitable zone. If the planet happens to transit, which has the probability $p_{trans} = 0.5\%(R_p/R_\oplus + R_{WD}/0.013R_\odot)/(a/0.02\text{AU})$, then there is a dip in the light curve lasting up to a few minutes duration $T_t = 3\text{min}(P/32\text{hr})(p_{trans}/0.5\%)\sqrt{1-b^2}$, where b is the dimensionless impact parameter of the transit ($b = 0$ for a central transit, $b = 1$ for grazing). Consequently, white dwarf star must be monitored for 32 hours with a cadence of less than a minute to rule out the presence of a transiting planet.

Since no theoretical predictions exist for the frequency of short period planets around white dwarfs, I instead define the frequency of planets, $\eta_\oplus$, which are in the CHZ ($a < 0.02$ AU) with masses within a factor of ten of Earth (this definition includes planets that are currently not in the WDHZ, but will be at some point in their lives). I then simulated two different surveys to determine the possible constraints on $\eta_\oplus$: (i) a survey of 20,000 white dwarfs with a global network of 1 meter telescopes; (ii) a survey of 10^7 white dwarfs with the Large Synoptic Survey Telescope. A minimum of $N_{wd} = 20,000(\eta_\oplus/1\%)^{-1}$ must be surveyed for an expected detection of 1 exoplanet; however, a larger number of planets should be targeted in a survey to obtain a measurement of $\eta_\oplus$ rather than a limit on it. If not all transiting planets are detected, then the number of stars surveyed must be greater.

In the first survey, I assumed a filter-free photometric telescope, and I included sky noise, detector noise, and shot noise, following.[24] Since the space density of white dwarfs is about 5×10^{-3} pc^{-3}, a survey out to 100 pc is required to obtain a sample of 20,000 white dwarfs. The surface density of white dwarfs to this distance is 0.5 deg^{-2}, so unless the telescope has a rather large field of view, one white dwarf will need to be surveyed at a time. This presents a large amount of required observing time: for 20,000 white dwarfs observed for 32 hr each, the total observing time is 73 years! This does not take into account observing inefficiencies since any given telescope can only observe at night ($\approx 50\%$) and weather reduces the amount of time available from any given site. In addition, to monitor a star for 32 hours requires a network of telescopes distributed in longitude; then a particular star can be handed off from telescope to telescope until it has been followed for 32 hours. Of course, weather at different sites might make this less feasible, so I assume a 50% weather inefficiency. This gives a total calendar time of 292 years; an even more prohibitive number. There are only two solutions to this problem: (1) build a large network of telescopes, as is being done by the Las Cumbres Observatory Global Telescope Network (LCOGT) as discussed in the talks by Martinez and Rosing; (2) build a large-format detector, such as the ATLAS concept discussed by Tonry.[25] If 20 one meter telescopes were devoted to this survey, then the calendar time would be about 15 years; any further reduction in time would require more telescopes, fewer target stars, or a shorter observing duration per star (the latter two cases would cause a decrease in the number of detected planets). The large format case would reduce the total observing time to $2deg^2/\Omega$. The ATLAS idea would need to have telescopes distributed longitudinally and latitudinally, such as the "World-wide Internet Survey Telescope" (WIST) concept discussed in Tonry (2011). If WIST consisted of six ATLAS telescopes distributed around the world in latitude and longitude with 40 square degrees per telescope, then the survey would take only 2.4 year (40 square degrees requires 1000 pointings to cover the sky; if the sky were continuously monitored from 6 sites at 25% efficiency, then to survey the entire sky for 32 continuous hours requires 29 months). Of course this has the additional advantage that it would be sensitive to all stars in the field with sufficient signal-to-noise, and thus might include hotter white dwarfs at larger distances, improving the sensitivity to the CHZ.

I have simulated the probability distribution of detected planets around white dwarfs out to 100 pc surveyed with 1 meter telescopes. Such a survey would need to be preceded by a reduced proper motion survey for white dwarfs to distinguish them from more distant main-sequence stars; such surveys are currently being carried out and have already started to yield large numbers of nearby cool white dwarfs.[26] I have run 10^4 simulations of a survey of 20,000 white dwarf stars, and I find that for $\eta_\oplus = 1\%$ the survey should find ≈ 1 transiting planet. I assumed that the planets are distributed uniform in log semi-major axis, that the planet frequency decreases with mass, and that there is a gradual cutoff from twice the Roche limit to the Roche limit. I find the interesting and surprising result that the survey would *favor the detection of planets with the temperature and radius of Earth.* This stands in stark contrast to other planet survey techniques: radial velocity and transit surveys of main sequence stars are biased towards the most massive, shortest period planets which are too hot and too massive to be habitable, while astrometric and microlensing surveys are biased towards massive, long period planets which are too cold and massive to be habitable (although microlensing is capable of probing the
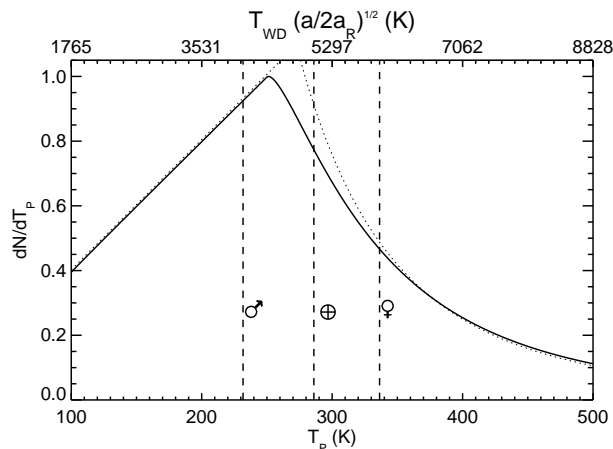
Figure 4. Temperature distribution of transiting planets orbiting white dwarfs assuming a uniform distribution of planets in $\log a$ and a cutoff within $2a_R$. The temperature distribution of white dwarfs is given by equation 2. The dotted lines are the analytic approximations for low temperature ($\propto T_p$) and high temperature ($\propto T_p^{-27/7}$). The effective temperatures of Venus, Earth and Mars are indicated assuming an albedo of 30%. The top axis shows the temperature of the white dwarf for a planet of T_p and distance a.

lower mass regime, the habitable zone is more of a problem). However, due to the coincidences discussed above, namely the similar size of white dwarfs to Earth and similar size of the CHZ and the Roche limit, transit surveys are biased towards detection of Earth-temperature and Earth-sized planets. Hotter planets orbit hotter stars. However, the number density of hot white dwarfs is (approximately) proportional to $dn/dT_{WD} \propto T_{WD}^{-27/7}$. The hottest planets orbit closest to these white dwarfs, which are also the easiest to detect as they have the largest transit probability, so the hottest detected planets have the same distribution: $dn/dT_p \propto T_p^{-27/7}$. The coolest planets orbit furthest from their host stars; since there is a sharp cutoff in the number of white dwarfs below the peak of the temperature distribution, and since $T_p \propto a^{-1/2}$, this causes the number of cool planets detected to decline as $dn/dT_p \propto a^{-1}(dn/da)(da/dT_p) \propto T_p$ for $T_p \ll T_\oplus$ and a uniform distribution of planets in $\log a$. If the temperature is very cool, it orbits far from the star and $P > 32$ hr, so there is a further decrease in probability $\propto P_0/P$, where P_0 is the duration of the observation (which I have assumed to be $P_0 = 32$ hr), so $dn/dT_p \propto T_p^4$ at these low temperatures. Figure 4 shows the distribution of transiting planets versus planet temperature assuming a uniform distribution in $\log a$ with a sharp cutoff at $2a_R$ and assuming all transiting planets are detected. As advertised, there is a cutoff in planet effective temperature towards low and high temperatures following the relations just derived, while the peak in the distribution is near the effective temperature of Earth due to the coincidence between the WDHZ at the peak of the white dwarf temperature distribution and twice the Roche limit; if the cutoff in planet semi-major axis had been chosen to be smaller, this peak would shift towards higher temperatures, and the axes in Figure 4 shift in proportion to $a_{min}^{-1/2}$. The distribution of *detected* transiting planets in practice cuts off more steeply at low temperatures due to the $P_0/P \propto T_p^3$ factor discussed above.[8]

In addition to favoring Earth-temperature planets, a volume-limited survey of white dwarfs favors detection of Earth-sized planets. This is due to the facts that small planets with $R_p \ll R_{WD}$ have a transit depth and signal-to-noise ratio that scales as $\propto (R_p/R_{WD})^2$, while large planets $R_p \gg R_{WD}$ have a transit depth of 100% and a duration $\propto R_p$ and signal-to-noise $\propto R_p^{1/2}$. Consequently there is a break in the signal-to-noise at $R_p \approx R_{WD} \approx R_\oplus$. Now, if the survey is targeting stars out to a distance for which Earth-like planets can be detected at the peak of the white dwarf luminosity function (this depends on the effective area of the telescopes being used), then this break will naturally occur at $R_p \approx R_\oplus$. If the size distribution of planets falls steeply enough towards large R_p, but not too steeply at small R_p, then the detected planet distribution will peak at $R_p \approx R_\oplus$. This occurs for the example of a 1 meter telescope surveying white dwarfs out to 100 pc, as shown in Agol (2011).
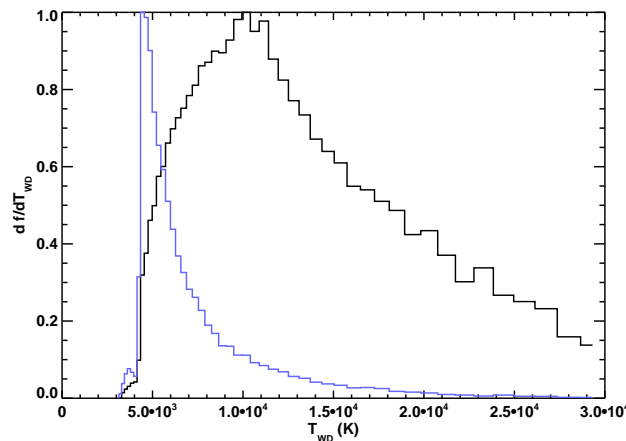
Figure 5. Temperature distribution of white dwarfs: volume integrated in blue, while magnitude-limited for LSST in black.

6. LARGE SYNOPTIC SURVEY TELESCOPE

A different strategy for detection of transiting planets presents itself for large-area survey telescopes such as Gaia, Pann-STARRs, or the Large Synoptic Survey Telescope (LSST). Since LSST will have the largest aperture and largest number of observations per field of these telescopes, I have simulated the detection rate for LSST. This survey is magnitude limited rather than volume limited; consequently the temperature distribution of white dwarfs detected with LSST peaks at about 10^4 K rather than 5000 K (Figure 5). For these simulations I assumed two 15 second r-band exposures are taken at 10^3 epochs with a $5 - \sigma$ detection limit at $r = 24.5$. I assumed planets are distributed uniformly in $\log a$, but in this case I assumed a cutoff at $a = a_R$ rather than $a = 2a_R$; for the planet mass I assumed a uniform distribution from 0.01 to 100 $M_\oplus$ with an Earth-composition mass-radius relation. Figure 6 shows the distribution of detected planet mass, and planet semi-major axis distribution for a simulated survey of white dwarfs with LSST. For $\eta_\oplus = 0.05\%$ I find that LSST should detect ≈ 1 transiting planet in the CHZ with at least 3 transits detected. Detection occurs for transiting planets for which at least three epochs with two exposures each epoch with a signal-to-noise $>7\sigma$ for each exposure. Assuming that each observation is taken at a random orbital phase for each transiting planet, for $N \gg 1$ observations, the probability that at least three epochs will be detected in eclipse is given by $p_3(x) = 1 - e^{-x}(1 + x + x^2/2)$, where $x = Nf$, f is the fraction of the period of the orbit which is detectable in transit at the chosen signal-to-noise cutoff. Typically $f \approx T_t/P \propto P^{-2/3}$ (if the transit is deep enough for a planet to be easily detected in transit), so this causes the detection rate to decline with period. Note that if rather than 3 transits I required n_t points in transit for a detection, then for $x \ll 1$ the probability of detection is $p_{n_t}(x) \propto x^{n_t} \propto P^{-2n_t/3}$, while for $x \to 1$, the probability approaches 100%. Thus, if I relaxed the detection criteria to $n_t =$ one or two points in transit, there would be more transiting planet candidates, but also possibly more false-positives; alternatively I could increase the number of observations per field to increase x. The total probability of transiting planet detection is the product of p_{trans}, the probability that a planet transits, and $p_{n_t}(x)$, the probability that a transiting planet is detected in transit n_t times. The simulated detected distribution is a convolution of these functions with the planet size distribution and signal-to-noise ratio of detected stars, but as expected, declines with increasing semi-major axis and decreasing planet mass as shown in Figure 6.

An additional issue is distinguishing white dwarf binaries from planetary transits. Figure 7 shows the light curve of a white dwarf binary with orbital period 16.0 hours, masses of 0.65 and 0.25 $M_\odot$, temperatures of 4469 K and 7227 K, and radii of 0.012 and 0.020 $R_\odot$. This binary was chosen at random from a distribution of white dwarf binaries generated with the BSE code.[8] Several features can be seen that distinguish this from a transiting planet: (1) the two eclipses have different depths; (2) the secondary eclipse is offset in time; (3) there is a photometric Doppler signal over the period of the orbit. These effects are subtle, and if the signal-to-noise of the lightcurve were poor enough this might be mistaken for an Earth-sized planet transiting a white dwarf with
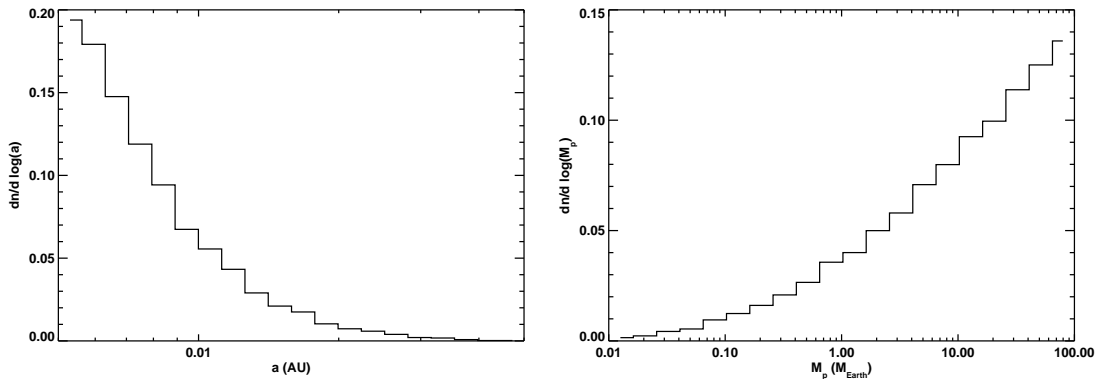
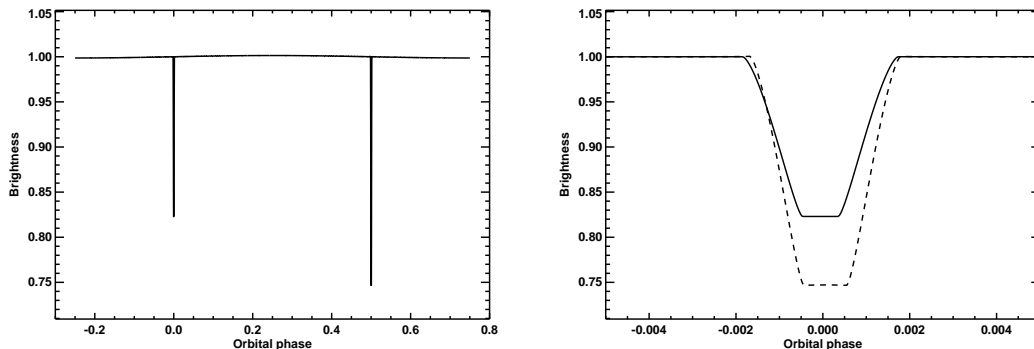Figure 6. Mass (left) and orbital distance (right) distributions of simulated planets detected by LSST.

Figure 7. Light curve of an eclipsing white dwarf binary as a function of orbital phase. Left is complete orbit; right shows the time near primary eclipse as well as the secondary eclipse shifted by half of the orbital period.

an orbital period of 8 hours. However, it is simply a matter of follow up with a larger telescope covering the entire orbital phase of 16 hours to determine that this is a white dwarf binary rather than a planet transiting a white dwarf.

7. CONCLUSIONS

Cool white dwarfs have ceased nuclear burning, but continue to release energy by gravitational settling and crystallization. In fact, these latter processes extend the duration of the white dwarf habitable zone. If planets can form in the WDHZ, this does not ensure habitability: if the planets form while the star is still hot, any volatile material may be lost, so the planet may not retain an atmosphere. Atmospheric models for planets which are tidally locked and illuminated by a cooling white dwarf are needed to determine when the atmosphere must be present on the planet to survive long term.

Other means of detection may be possible. At the conference Reed Riddle suggested that the Kepler satellite might be able to search for planets transiting cool white dwarfs. However, due to the small fraction of the sky covered by Kepler, $\approx 0.25\%$, and the bright magnitude limit of Kepler, $V < 16$, there are few cool white dwarfs that could be monitored within the field of view. Since the white dwarf transit is so deep, a satellite does not have much advantage over ground-based surveys, except for continuous coverage, while a network of wide-field robotic telescopes, such as WIST, could carry out such a survey in a time comparable to the Kepler survey at much less cost. In the Rayleigh-Jeans limit, the flux ratio approaches $(T_p/T_{WD})(R_p/R_{WD})^2 \approx 2.9\%$ for an Earth twin orbiting a white dwarf at the peak of the luminosity function. The planet could be detected by measuring the deviation from a blackbody spectrum; however, this requires precise photometric calibration and may be indistinguishable from a dust ring orbiting at the same distance. Since a planet should be tidally locked, the periodic flux variation as the day and night rotate in and out of view will distinguish a planet from a dust ring.

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This approach has the advantage that it does not require the planet to transit. However, *JWST* unfortunately does not have the sensitivity due to background flux caused by the star shade.

The remarkable coincidence between the white dwarf habitable zone at the peak of the white dwarf luminosity function and twice the Roche limit means that a transit survey for planets around the nearest white dwarfs will be *biased towards detecting Earth-temperature planets.* This, of course, assumes that there are any planets there at all; if they form out of a disk, the disk may spread too much to form close in planets (although further migration might bring the planet back inward). Also, interaction with the star's magnetic field may cause orbital evolution of the planet; the significance of this effect has yet to be determined. The higher orbital velocity may cause more energetic impacts by comets or asteroids, which may have a beneficial or detrimental affect on any life that might form on such a planet. Consequently, much work remains to be done on this problem, both observationally and theoretically, to determine if white dwarfs might be a safe haven for Earth-like planets.

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