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THE HABITABILITY AND DETECTION OF EARTH-LIKE PLANETS ORBITING COOL WHITE DWARFS

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ABSTRACT

Since there are several ways planets can survive the giant phase of the host star, we examine the habitability and detection of planets orbiting white dwarfs. As a white dwarf cools from 6000 K to 4000 K, a planet orbiting at 0.01 AU would remain in the continuous habitable zone (CHZ) for ∼8 Gyr. We show that photosynthetic processes can be sustained on such planets. The DNA-weighted UV radiation dose for an Earth-like planet in the CHZ is less than the maxima encountered on Earth, and hence non-magnetic white dwarfs are compatible with the persistence of complex life. Polarization due to a terrestrial planet in the CHZ of a cool white dwarf (CWD) is 10^2 (10^4) times larger than it would be in the habitable zone of a typical M-dwarf (Sun-like star). Polarimetry is thus a viable way to detect close-in rocky planets around white dwarfs. Multi-band polarimetry would also allow us to reveal the presence of a planet atmosphere, providing a first characterization. Planets in the CHZ of a 0.6 $M_\odot$ white dwarf will be distorted by Roche geometry, and a Kepler-11d analog would overfill its Roche lobe. With current facilities a super-Earth-sized atmosphereless planet is detectable with polarimetry around the brightest known CWD. Planned future facilities render smaller planets detectable, in particular by increasing the instrumental sensitivity in the blue.

Key words: planets and satellites: detection – techniques: polarimetric – white dwarfs

Online-only material: color figures

1. INTRODUCTION

The search for habitable Earth-like planets is a major contemporary goal of astronomy. As the detection of exoplanets is biased toward systems with small differences in mass, radius, and luminosity between star and planet (e.g., Haswell 2010), M-type main-sequence stars have become prime targets in the search of Earth-like planets in the habitable zone. M-dwarfs evolve slowly: their planets might remain within a continuously habitable zone (CHZ),[7] i.e., harboring surface liquid water, for several Gyr, providing ample time for the advent of life on a rocky planet.

With an effective temperature ($T_{\rm eff}$) $\leqslant$ 6000 K, cool white dwarfs (CWDs) are also promising hosts of rocky planets in the habitable zone. White dwarfs initially cool down rapidly, with temperature decreasing by thousands of degrees in ∼3 Gyr (Salaris et al. 2010). At $T_{\rm eff} \sim 6000$ K, crystallization slows the cooling process. This produces a habitable zone that endures for up to 8 Gyr (Agol 2011), well in excess of the time required for life to arise on Earth. White dwarfs provide a stable luminosity source without the potentially damaging radiation produced by stellar activity in M-dwarfs. A planet orbiting close to a white dwarf would synchronize within 1000 yr and would have a stable orbit, as the planet would not raise tides on the star (Agol 2011).

The major issue for the presence of a planet close to a white dwarf is survival during the host star's giant phase. Faedi et al. (2011) review several mechanisms which would result in a planet orbiting a white dwarf. Charpinet et al. (2011) found two Earth-sized bodies in a very close orbit (∼0.007 AU) around a post-red-giant star proving that planet-sized objects can survive the post-main-sequence evolution phases of their host star. Further evidence for the existence of rocky bodies close to white dwarfs comes from the presence of metallic lines (e.g., Mg and Fe) in the spectra of DZ white dwarfs (Zuckerman et al. 2010). Heavy metals in the atmospheres of these stars can only be explained by atmospheric "pollution" caused by the accretion of terrestrial-like planets or planetesimals (see, e.g., Farihi et al. 2010; Melis et al. 2011; Klein et al. 2011; Gänsicke et al. 2012).

The low luminosity of CWDs creates a habitable zone at only ∼0.01 AU, 10 times closer than for M-dwarfs. This facilitates the detection of small bodies orbiting white dwarfs. Agol (2011) showed that transits of Mars-sized planets in the white dwarf CHZ would be 1% deep, easily detectable with present-day ground-based facilities, even for rather faint stars, though searches for planetary companions to white dwarfs have so far been unsuccessful (Friedrich et al. 2007; Faedi et al. 2011).

Polarimetric techniques can also be used to discover and characterize exoplanets. As shown by Seager et al. (2000) and Stam (2008), as a planet orbits around the host star, the amount of polarization varies regularly, showing maxima when the planet is near quadrature. The amplitude of the variation depends mainly on the orbital inclination, i, with no polarimetric variability for a face-on orbit. The detection and measurement of regular polarization variations permit the discovery of exoplanets, with an efficiency dependent on i, similar to that of the radial velocity planet detections. Spectropolarimetry of planet-hosting stars could characterize

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[7] Range of planet orbital distances at which the planet is habitable for a minimum of 3 Gyr.

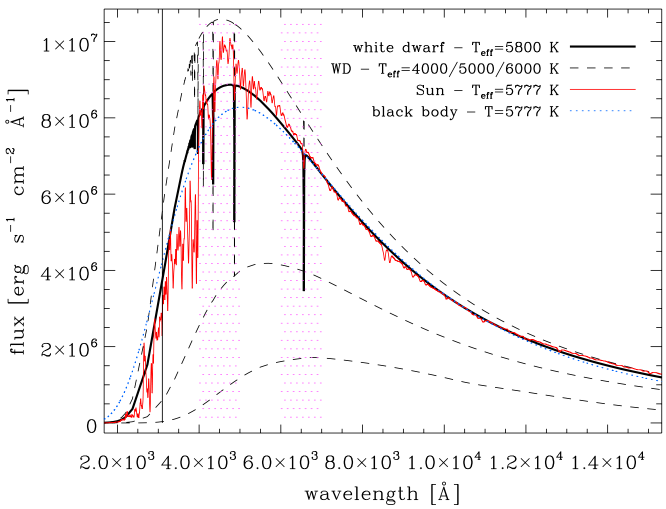

Figure 1. Comparison between white dwarf and solar synthetic emergent fluxes per unit area at the emitting photosphere. The thick line: 5800 K hydrogen white dwarf; dashed lines: hydrogen white dwarfs with $T_{\rm eff} = 4000$, 5000, and 6000 K. With decreasing temperature the hydrogen lines weaken until they almost disappear. Thin continuous red line: synthetic fluxes of the Sun calculated with MARCS models; dotted line: a 5777 K, blackbody, i.e., with the Sun's $T_{\rm eff}$. The vertical black line at 3100 Å shows the limit for the DNA damaging fluxes. The shaded areas show the wavelengths playing a major role in the process of photosynthesis.

(A color version of this figure is available in the online journal.)

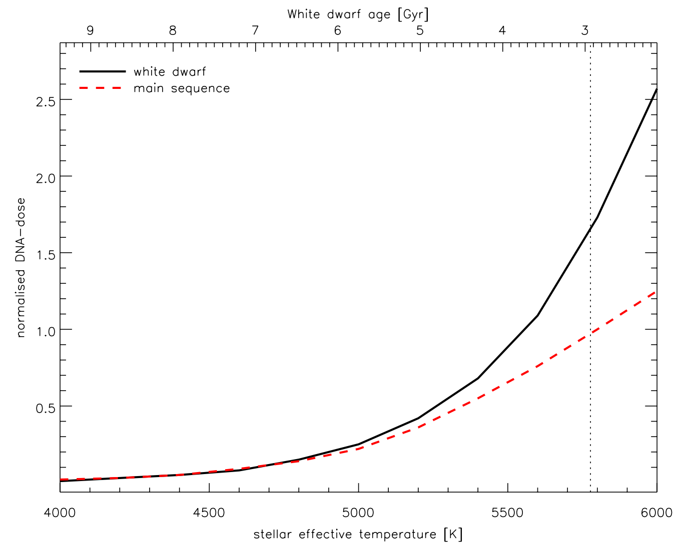

Figure 2. DNA-weighted dose for an Earth-like planet orbiting in the habitable zone of a CWD (black continuous line) and of main-sequence stars (dashed red line). In the white dwarf case we adopted an orbital separation of 0.01 AU, while in the main-sequence case we adopted a varying orbital separation to maintain a constant planet equilibrium temperature. The DNA-weighted dose is normalized to that of present Earth. The upper x-axis indicates the white dwarf age, at a given temperature.

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the atmosphere of an exoplanet (Stam 2008), something now only possible for transiting exoplanets.

2. IS LIFE POSSIBLE ON EARTH-LIKE PLANETS IN THE WHITE DWARF CHZ?

It is important to establish whether CWDs have a flux distribution which would allow the advent of complex life on Earth-like planets orbiting in the CHZ. Consider an Earth-like planet with surface liquid water and a nitrogen-dominated atmosphere,[8] orbiting in the white dwarf CHZ. Major requirements for the persistence of life, as we know it on Earth, are sufficient suitable radiation to sustain photosynthesis and a UV flux low enough to prevent fatal Deoxyribonucleic acid (DNA) damage.

Figure 1 shows a comparison between the synthetic surface fluxes of CWDs with pure hydrogen atmospheres at four different $T_{\rm eff}$, the Sun (from Gustafsson et al. 2008), and a 5777 K blackbody. We used CO white dwarfs of radius 0.013 $R_{\odot}$and of mass 0.6 $M_{\odot}$. The model fluxes were computed by the stellar atmosphere code developed by Kowalski (2006) and Kowalski & Saumon (2006).

The wavelength ranges playing a role in the photosynthetic processes (e.g., McCree 1972) are blueward of 5000 Å and between 6000 and 7000 Å. The fluxes integrated over these wavelengths for a 5800 K white dwarf and the Sun are almost identical. This direct comparison is valid because the angular diameter of a CWD, as seen from the CHZ, is similar to that of the Sun, as seen from Earth (Agol 2011). Raven (2007) concluded that photosynthesis can occur on exoplanets in the habitable zone of M-dwarfs. The photosynthetic relevant flux intercepted by a planet in the CHZ of a 4000 K white dwarf is larger than that intercepted by the same planet in the habitable zone of a typical M-dwarf. These comparisons show that photosynthesis would be both feasible and efficient on planets orbiting in the white dwarf CHZ.

Fluxes shortward of ∼3100 Å (see Figure 1) can potentially damage DNA molecules. To check whether the UV radiation emitted by a CWD is a threat to the formation and persistence of DNA molecules, we compared the DNA dose expected for an Earth-like planet in the white dwarf CHZ with that experienced on Earth. We adapted a radiative transfer model developed for application to Mars (Patel et al. 2004) to create a simplified Earth-atmosphere model and determine the amount of UV radiation received at the planet's surface as a function of white dwarf temperature. To provide an effective comparison as a function of stellar temperature, we modeled the same conditions for a hypothetical Earth-like planet around a main-sequence star, with the semimajor axis varied as a function of temperature, keeping the "main-sequence exoplanet" within the habitable zone. This comparison is shown in Figure 2. We used a standard terrestrial atmospheric composition, with a nominal ozone abundance of 300 DU. This is a first-order approximation as we neglect important factors such as clouds. To interpret the surface irradiances in a biological context, we applied a DNA action spectrum (Setlow & Doyle 1954; Munakata et al. 1991) to the modeled spectra to define a DNA-weighted dose for each case. DNA is used here as a generic model of the response of carbon-based organisms to UV.

The DNA-weighted UV dose encountered at the surface of an Earth-like planet in the white dwarf CHZ becomes comparable to that of an exoplanet in the habitable zone of a main-sequence star at approximately 5000 K. Interestingly, present-day solar conditions produce an average dose on Earth a factor of only 1.65 less than that for a white dwarf with solar $T_{\rm eff}$. Varying terrestrial atmospheric conditions at times produce DNA-weighted doses on Earth as high as that on a CWD planet. Figure 2 also clearly demonstrates that the DNA-weighted dose for a hypothetical Earth-like planet around a CWD is remarkably benign from

[8] Nitrogen would be a major constituent also of a lifeless Earth (Kasting et al. 1993).

Table 1
Polarization Obtained for a Planet in the CHZ of a $T_{\rm eff} = 5000$ K White Dwarf

	Polarization at 4000 Å			Polarization at 5000 Å			Polarization at 6000 Å		
	Orbital Separation in AU			Orbital Separation in AU			Orbital Separation in AU		
$R_\oplus$	0.0054	0.01	0.02	0.0054	0.01	0.02	0.0054	0.01	0.02
0.5	6.6×10^{-7}	1.9×10^{-7}	4.8×10^{-8}	3.2×10^{-7}	9.3×10^{-8}	2.3×10^{-8}	1.4×10^{-7}	4.1×10^{-8}	1.0×10^{-8}
1.0	2.6×10^{-6}	7.7×10^{-7}	1.9×10^{-7}	1.3×10^{-6}	3.7×10^{-7}	9.3×10^{-8}	5.7×10^{-7}	1.7×10^{-7}	4.1×10^{-8}
2.1	1.2×10^{-5}	3.4×10^{-6}	8.4×10^{-7}	5.6×10^{-6}	1.6×10^{-6}	4.1×10^{-7}	2.5×10^{-6}	7.3×10^{-7}	1.8×10^{-7}
1.0	Sun at 1 AU: 7.7×10^{-11}			Sun at 1 AU: 3.7×10^{-11}			Sun at 1 AU: 1.7×10^{-11}		
1.0	M-dwarf at 0.1 AU: 7.7×10^{-9}			M-dwarf at 0.1 AU: 3.7×10^{-9}			M-dwarf at 0.1 AU: 1.7×10^{-9}		

Notes. The polarization is given as a function of planet radius (in $R_\oplus$), orbital separation (in AU), and wavelength (in Å). A planet of 0.5 $R_\oplus$ would be about as large as Mars, while 2.1 $R_\oplus$ is the typical size of a super-Earth. The orbital separations are the minimum and maximum limits, and center of the CHZ. For comparison, in the two bottom lines, we list the polarization obtained for an Earth-size planet in the habitable zone at 1 AU from the Sun ($T_{\rm eff} = 5777$ K) and at 0.1 AU from an M-dwarf ($T_{\rm eff} = 3200$ K). For all calculations we assumed a phase angle of 68°, where the polarization is at maximum.

an astrobiological perspective, for an extremely long period of time.

We therefore conclude that a CWD is a plausible source of energy for the advent and persistence of complex life, as we know it on Earth. We have to point out that about 10% of all white dwarfs host magnetic fields (Putney 1996; Landstreet et al. 2012). A planet in the CHZ of a magnetic white dwarf would constantly orbit inside the star's magnetic field, which, at 0.01 AU, can be as large as a few kG. Such a field, interacting with biological matter, might prevent the persistence of life. This issue is the subject of a forthcoming study and for now we assume the potential planet-hosting white dwarf to be non- (or weakly) magnetic. This assumption also implies the absence of magnetic drag, which would cause the planet orbit to decay.

In the previous analysis, we also assumed an atmosphere-bearing planet, although the initial high temperature of the white dwarf would cause the atmosphere of a close-in planet to evaporate. Various mechanisms, such as planet migration and crustal outgassing, could however replenish an atmosphere.

3. POLARIZATION FROM AN EARTH-LIKE PLANET IN THE WHITE DWARF CHZ

Using white dwarf model fluxes from Section 2 and models of reflected light and degree of polarization from Stam (2008), we calculated the amount of polarized light reflected by the atmosphere of an unresolved Earth-sized planet in the CHZ of CWDs. Throughout we adopt $\alpha = 68^\circ$ (angle between star and Earth as seen from the planet) and a cloud-free Lambertian planet surface with a wavelength independent albedo of 1.0 (labeled as "L10" by Stam 2008). This is an idealized case: for comparison Earth's albedo is ≈0.3 (Charlson et al. 2005), though a snowball Earth might have an albedo of ≈0.85. Assuming an orbit inclination angle of 90°, the polarization as a function of wavelength (λ) and phase angle, $P_{\rm obs}(\lambda, \alpha)$, seen by a distant observer is

$$P_{\rm obs}(\lambda, \alpha) = \frac{F_* \frac{\pi r^2}{4\pi d^2} b_1(\lambda, \alpha)}{F_* \left(1 + \frac{\pi r^2}{4\pi d^2} a_1(\lambda, \alpha)\right)}, \quad (1)$$

where $a_1(\lambda, \alpha)$ and $b_1(\lambda, \alpha)$, varying between 0 and 1.2, are two elements of the planet scattering matrix (e.g., Stam et al. 2006), r and d are respectively the planet radius and orbital separation, and F_* is the stellar flux. The numerator represents the polarized flux reflected by the planet, while the denominator corresponds to the total flux emitted by the system ($\approx F_*$ as $(r^2/d^2) << 1$).

Following Stam (2008), $b_1(\lambda, \alpha)$ is maximum at $\alpha = 68^\circ$, therefore the maximum polarization becomes

$$P_{\rm obs,max}(\lambda) \approx \frac{r^2}{d^2}\frac{1}{4} b_1(\lambda, \alpha = 68^\circ). \quad (2)$$

Figure 3 shows the maximum polarization, as a function of wavelength, produced by an unresolved Earth-sized planet orbiting at a distance of 0.01 AU from a 5000 K white dwarf. We examined the dependence of the polarization on orbital separation and planet radius, taking the polarization at 4000 Å. The results are shown in the lower panels of Figure 3.

Table 1 gives the polarization at three different wavelengths, produced by Mars-sized, Earth-sized, and super-Earth-size planets orbiting around a 5000 K white dwarf. Three different distances from the host star were used: 0.0054, 0.01, and 0.02 AU, representative of the inner edge, center, and outer edge of the white dwarf CHZ, respectively. Table 1 also gives the polarization of unresolved Earth-sized planets orbiting in the habitable zone of a Sun-like star and of a typical M-dwarf ($T_{\rm eff} = 3200$ K).

Table 1 shows that the polarization produced by an unresolved Earth-sized planet at 1 AU from a Sun-like star is of the order of 10^{-10}. For a typical M-dwarf, the habitable zone is at a distance of ∼0.1 AU (Selsis et al. 2007), therefore the amount of polarization is the order of 10^{-8}. The white dwarf CHZ is at 0.01 AU, consequently the amount of polarization is the order of 10^{-6}. The polarization signal of any planet in the white dwarf CHZ is therefore larger than that of a comparable planet in the habitable zone of any other type of star, excluding brown dwarfs, where low luminosity and high stellar activity most likely preclude life.

4. PHOTOMETRIC VARIATIONS

The planet will cause a variability of the total flux larger than that of the polarized flux. At phase angle $\alpha = 0$, (orbital phase 0.5, superior conjunction of the planet) the full disk of a planet at $i = 90^\circ$ will be illuminated producing a photometric maximum. The photometric minimum occurs at inferior conjunction of the planet ($\alpha = 180^\circ$), with intermediate fluxes at quadrature ($\alpha = 90^\circ$), where the polarimetric maxima occur. The detailed photometric light curve would depend on the planet scattering matrix, but the reflected flux will be roughly proportional to the illuminated area.

Photometric variability can, however, arise from many different mechanisms, so a planet detection based on photometry alone would not be credible. Since cool non-magnetic white

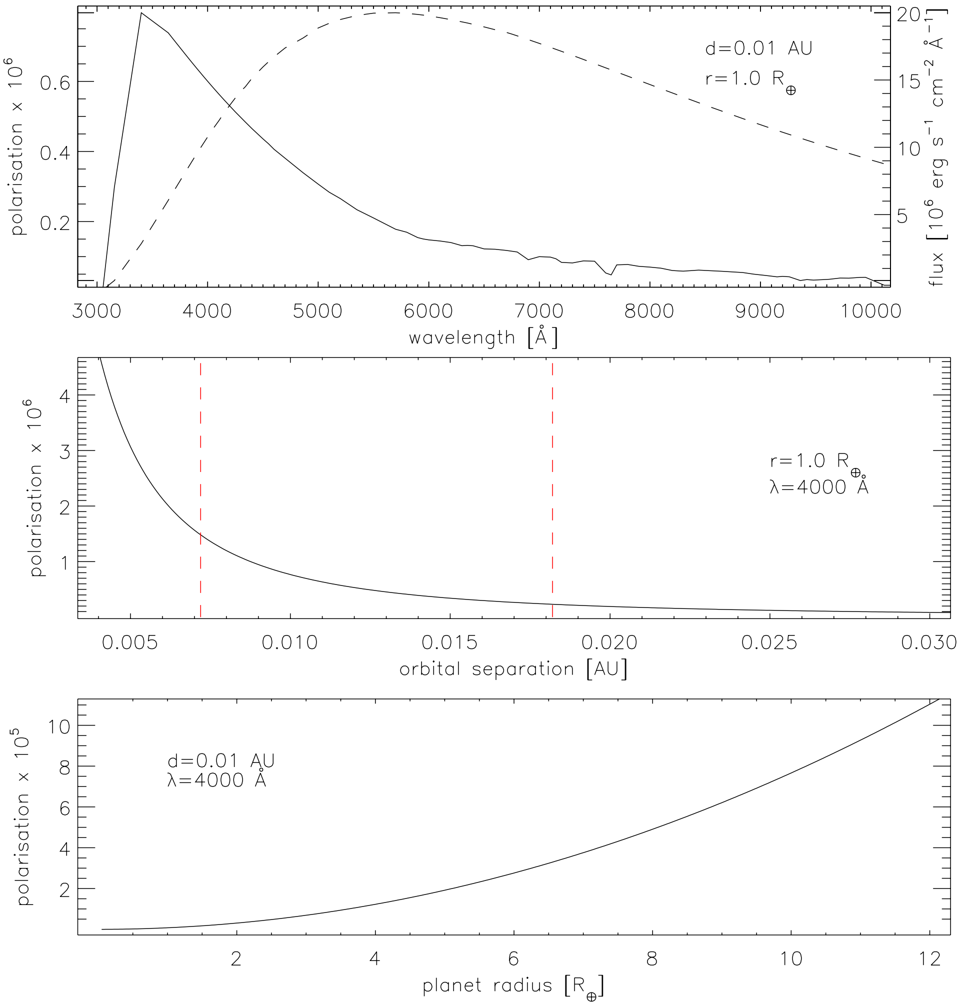

Figure 3. Top panel: polarization in the visible region as a function of wavelength for an Earth-sized planet at a distance of 0.01 AU from a 5000 K white dwarf. The white dwarf synthetic flux is shown by a dashed line (scale on the right-hand side). Middle panel: polarization at 4000 Å from an Earth-sized planet as a function of distance from a 5000 K white dwarf. The dashed vertical lines indicate the limits of the habitable zone, calculated following Selsis et al. (2007), using the Venus and early-Mars criteria. Bottom panel: polarization at 4000 Å as a function of planet radius placed at a distance of 0.01 AU from a 5000 K white dwarf.

(A color version of this figure is available in the online journal.)

dwarfs are expected to have little intrinsic photometric variability, a small photometric signal phased appropriately with the polarimetric variability could serve to confirm a polarimetric planet detection.

Planets in the CHZ of CWDs fill a substantial fraction of their Roche lobes. We quantified this numerically, calculating the Roche geometry for planets orbiting at 0.01 AU from 0.6 $M_\odot$ white dwarfs. Planets with masses and radii similar to Earth, Corot-7b, Kepler-10b, and Kepler-11b are all noticeably distorted from spherical: the ratio of their illuminated area at maximum and at quadrature is 1.95, 1.95, 1.97, and 1.90, respectively. A spherical planet would have a ratio of exactly 2.0. A bloated planet similar to Kepler-11d would overfill its Roche lobe, and would thus lose its outer layers until it exactly fills the critical equipotential surface. It would present an enlarged teardrop-shaped cross-section at quadrature, with the illuminated area at photometric maximum being only 1.52 times that at quadrature.

5. REFLECTED LIGHT SEARCHES FOR PLANETS IN THE WHITE DWARF CHZ

Agol (2011) made the case for transit searches targeting white dwarfs. Planets in the CWD habitable zone would also reflect a relatively large fraction of the stellar flux, producing also a relatively strong polarization signal, as quantified in Section 3.

The CWD habitable-planet orbital separation, a, precludes planet detection by direct imaging unless the distance, d, satisfies

$$\frac{d}{\mathrm{pc}} \leqslant 1.2\left(\frac{a}{0.01\,\mathrm{AU}}\right)\left(\frac{400\,\mathrm{nm}}{\lambda}\right)\left(\frac{D}{10\,\mathrm{m}}\right), \tag{3}$$

where D is the aperture determining the diffraction limit and assuming the use of a coronagraph working at an angular separation of λ/D. For the fiducial numbers above, even Proxima Centauri, the closest known star is too distant. Similarly, *Gaia*'s astrometric precision could only detect an Earth-like planet in the CHZ for 0.6 $M_\odot$ white dwarfs less than half the distance of Proxima Centauri. Microlensing, too, is only sensitive to planets with wide orbits. For hydrogen and helium white dwarfs (the most common), the radial velocity detection of Earth-like planets in the white dwarf CHZ is precluded as the few available H and He lines do not facilitate the required precision of <1 m s^{-1}. Reflected light (with ellipsoidal variation) and polarization seem to be the most viable ways to detect close-in non-transiting rocky planets orbiting white dwarfs.

Interstellar material could generate a much larger polarization signal, but constant with time, hence easily to disentangle by that

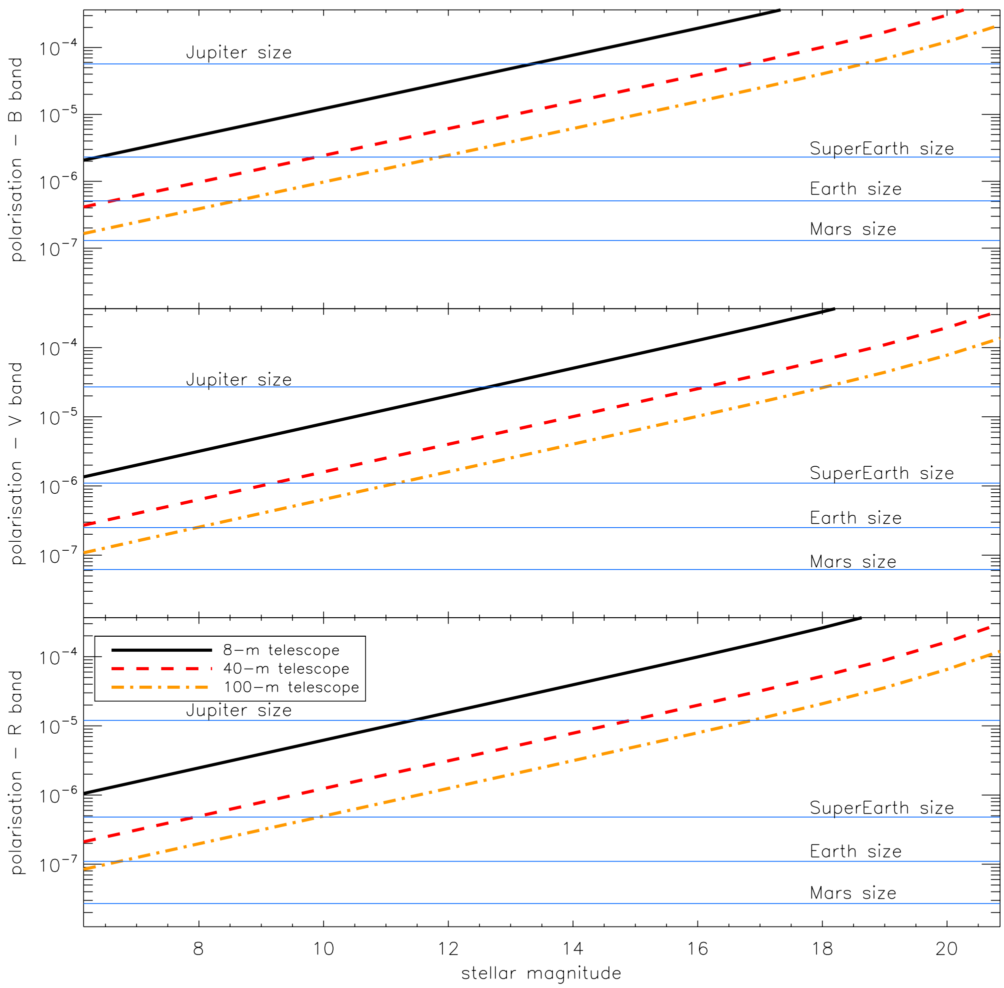

Figure 4. Amount of polarization detectable at 3σ in the B (top), V (middle), and R (bottom panel) bands, as a function of stellar magnitude, with a hypothetical FORS-like polarimeter mounted at an 8 m (black full line), a 40 m (red dashed line), and a 100 m (yellow dash-dotted line) telescope, and an exposure time of 2.5 hr. The horizontal lines show the amount of polarization emitted in the three bands by planets of different sizes, orbiting at 0.01 AU from a $T_{\rm eff} = 5000$ K white dwarf. Note that the amount of polarization emitted by a Jupiter-sized planet has to be taken with caution as we employed models by Stam (2008), which are not designed for gas giants.

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due to a planet. Magnetic fields and circumstellar disks could be responsible for small and time-dependent linear polarization signals (although with a different wavelength dependency). Detection of polarimetric variability would not be sufficient to warranty planet detection. This should be supported by the combined analysis of the photometric and polarimetric curves as function of wavelength.

To detect linear polarization at a 3σ level in a rocky planet in the white dwarf CHZ, we require observations at a signal-to-noise ratio (S/N) of $\sim10^6$. White dwarfs are faint, constituting the largest obstacle to the planet detection. Furthermore, the very short planet orbital period ($\sim$12 hr in the CHZ) limits integration times to 2–3 hr.

Figure 4 shows the polarization detectable with a hypothetical polarimeter (with transmission characteristics similar to those of the FORS2 instrument at the ESO/Very Large Telescope; VLT), mounted at an 8 m (e.g., VLT), 40 m (e.g., E-ELT), and 100 m (e.g., OWL) telescope, in the B, V, and R bands, as a function of stellar magnitude. We assumed a fixed integration time of 2.5 hr, a blackbody radiator of 5000 K, new moon, and an airmass of 1.6. As shown by Berdyugina et al. (2011), the B band compares well with the V and R bands, because of the larger polarization emitted by the planet at shorter wavelengths, despite lower flux, and CCD sensitivity.

The brightest single CWD is WD 0046+051 ($T_{\rm eff} = 6220$ K), with a magnitude of $V \sim 12.4$ (Holberg et al. 2008). Current observing facilities are capable of a 3σ detection only of a Jupiter-sized planet in the CHZ of this star using an exposure time of 2.5 hr. Future observing facilities could detect super-Earth-sized planets (between 2.0 and 2.5 $R_\oplus$) in the CHZ. Known white dwarfs with a temperature below 6000 K are all of $V \geqslant 14$ mag and Figure 4 shows that for them even a 40 m telescope barely detects super-Earth-sized planets in the CHZ via polarimetry. This situation could be easily improved by using an instrument with a higher sensitivity in the blue.

For an atmosphereless planet, the amount of polarization would be color independent (Bagnulo et al. 2006). Multi-band polarimetry could then be used to identify the presence or the absence of a planetary atmosphere. For an atmosphereless planet, we could therefore integrate over the whole visible region with a considerable gain in S/N. This strategy will permit 3σ detection of super-Earth-sized planets in the CHZ of a V=12 mag CWD with present-day observing facilities.

Non-magnetic white dwarfs have the characteristics necessary to host the advent of life on planets orbiting in the continuous habitable zone. A planet in the CHZ has 100 (10000) times the linear polarization of the same planet orbiting in the habitable zone of an M-dwarf (Sun-like star). The relatively high polarization of planets orbiting in the white dwarf CHZ and the extreme stability of the linear polarization emitted by non-magnetic white dwarfs make polarimetry a potentially effective way to detect close-in planets. In the case of atmosphere-bearing planets, the lack of bright white dwarfs coupled with the short orbital period of planets in the CHZ, only permit detections of Jupiter-sized planets with current observing facilities (8 m telescope) and super-Earth-sized planets with future facilities (40 m and 100 m telescopes). For atmosphereless planets, the observational capabilities allow detection of super-Earth-sized planets in the CHZ for the brightest known CWD.

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