Detecting bio-markers in habitable-zone earths transiting white dwarfs

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27 August 2013

ABSTRACT

The characterization of the atmospheres of habitable-zone Earth-mass exoplanets that transit across main-sequence stars, let alone the detection of bio-markers in their atmospheres, will be challenging even with future facilities. It has been noted that white dwarfs (WDs) have long-lived habitable zones and that a large fraction of WDs may host planets. We point out that during a transit of an Earth-mass planet across a WD, the planet’s atmospheric transmission spectrum obtains a much higher contrast over the stellar background compared to a main-sequence host, because of the small surface area of the WD. The most prominent bio-marker in the present-day terrestrial atmosphere, molecular oxygen, is readily detectable in a WD transit via its A-band absorption at $\sim 0.76 \mu m$. A potentially life-sustaining Earth-like planet transiting a WD can be found by assembling a suitable sample of $\sim 500$ WDs and then surveying them for transits using small telescopes. If and when a transiting case is found, the $O_2$ absorption in the planetary atmospheric transmission spectrum would be detectable with the James Webb Space Telescope (JWST) in about 5 hours of total exposure time, integrated over 160 2-minute transits. Characterization of the planet atmosphere using other tracers such as water vapour and $CO_2$ will be considerably easier. We demonstrate this future discovery space by simulating a possible transmission spectrum that would be obtained with JWST.

Key words: planets: extrasolar – white dwarfs:

1 INTRODUCTION

The discovery of the first transiting exoplanet, HD209458 (Charbonneau et al. 2000) was quickly followed by a measurement and characterization of the planet’s atmospheric transmission spectrum (Charbonneau et al. 2002). Spectroscopic observations of this type provide invaluable probes of planetary physics, formation, and evolution. The measurement, however, is difficult because of the tiny contrast, $\sim 10^{-3} - 10^{-4}$, between the signal (the absorption lines in the light transmitted through the planet atmosphere) and the background (the unobstructed light from the host star). In HD209458 the observation was possible owing to the closeness (and hence brightness, $V = 7.7$ mag) of the star, combined with the stability provided by the Hubble Space Telescope. Only a few measurements of this kind have been successful to date (e.g. Tinetti et al. 2007; Redfield et al. 2008; Zhou & Bayliss 2012; see also Berta et al. 2012 for a recent null result). Future prospects for exoplanet transmission spectra have focused on the capabilities of the James Webb Space Telescope (JWST), and on space mission concepts such as Darwin and the Terrestrial Planet Finder.

JWST and other future telescopes may indeed be able to extend exoplanet atmospheric measurements down to planet masses of a few earths, particularly in the habitable zones around M-stars (e.g., Webb & Wormleaton 2001; Ehrenreich et al. 2006; Beckwith 2008; Kaltenegger & Traub 2009; Deming et al. 2009; Rauer et al. 2011; Pallé et al. 2011; Benneke & Seager 2012), though at the price of many tens to hundreds of hours of total exposure time, integrated over many transits, and only if such transiting planets exist around nearby M-dwarfs that are bright enough. Current studies of potentially detectable species in Earth-like atmospheres have focused on water vapour, methane, $CO_2$, $O_2$, and ozone in the near- to mid-infrared (IR) part of the spectrum. The detection of bio-markers that signal the presence of life on a planet, such as ozone, $O_2$, or even the “red edge” of chlorophyll, is more challenging, and most studies (e.g.

1 http://www.jwst.nasa.gov/
2 http://www.esa.int/Our_Activities/Space_Science/Darwin_overview/
3 http://science.nasa.gov/missions/tpf/
von Paris et al. (2013) have expressed pessimistic prospects for their detection even with post-JWST space missions currently considered.

On Earth, O$_2$ is the prime bio-marker, being produced almost exclusively by photosynthesis. The terrestrial atmosphere had a 2-4% oxygen abundance since an age of $\sim 2$ Gyr, with a rise to the present-day levels of 20-30% starting only after another $\sim 1.5$ Gyr, probably due to the appearance of large vascular land plants (e.g., Canfield 2005; Goldblatt et al. 2006; Kump et al. 2011). If all life on Earth ceased, abiotic processes would remove all oxygen from the atmosphere within $\sim 10^9$ yr.

Ozone, with a strong signature at 9.6$\mu$m, is an indirect bio-marker, produced on Earth via UV illumination of O$_2$ but it can also form via abiotic processes, and may be masked by CO$_2$ absorption features (e.g., von Paris et al. 2011; 2013). Direct detection of O$_2$ in exoplanet atmospheres has been considered mainly via the rather weak absorption signal at 1.27$\mu$m (e.g., Fujii et al. 2012, but see Palle et al. 2009, where the feature is strengthened by oxygen dimers in refraction-enhanced lower-atmosphere spectra), and via the O$_2$ absorption bands in the red part of the optical spectrum – the A, B and $\gamma$-bands, centered at $\sim 0.76$ $\mu$m, 0.69 $\mu$m, and 0.63 $\mu$m, respectively.

Agol (2011) noted that white dwarfs (WDs) have long-lived habitable zones. If these zones host Earth-mass planets, the planets could potentially harbour life. Whereas no planets have yet been detected around a WD, there is some circumstantial evidence for their existence. At least one example of a stellar remnant, a neutron star, has a planetary system (Wolszczan & Frail 1992). Sion et al. (2009) estimated, based on the presence of photospheric metals in at least 15% of WDs, which possibly results from the accretion of debris disks, that a similar fraction of WDs could host terrestrial planets or asteroids. A similar analysis by Zuckerman et al. (2010) suggested a fraction as high as 30%. Infrared excess emission has been found in several tens of such polluted WDs, and has been interpreted as circumstellar dust rings produced by the tidal disruption of rocky planets or planetesimals, and subsequently accreted onto the WD, which then displays related elemental signatures (Zuckerman & Becklin 1987; Kilic et al. 2005, 2006; Jura et al. 2009; Farihi et al. 2009, 2010ab,2012). In several cases (Zuckerman et al. 2007; Klein et al. 2011; Dufour et al. 2012), the WD atmospheric abundance pattern has been studied in detail, and found to be similar to the outer composition of rocky bodies in the Solar System. Gaensicke et al. (2006, 2007) identified double-peaked emission from metal-rich gas disks around two WDs, with the metals thought to result from sublimated solids.

A small planet within several AU cannot survive the asymptotic giant branch phase, and therefore needs to migrate in from a wider orbit to the habitable zone, after the WD has formed. Even then, Barnes & Heller (2012) and Nordhaus & Spiegel (2012) have emphasized that the tidal heating of the planet, until it had achieved full circularization and synchronization, would lead to full loss of any water and volatiles present. We note, however, that the young Earth was also a hot and dry place, but volatiles and water were then delivered to it by a barrage of comets. The comet impact rate then decreased to its present low level, greatly lowering the biological damage of such impacts. It is not implausible that such post-formation volatile delivery also could take place on an earth-like planet in a WD’s habitable zone, perhaps driven by the same scattering process that drove the planet itself to migrate inward after the formation of the WD.

Di Stefano et al. (2010), Drake et al. (2010) and Faedi et al. (2011) noted that, owing to the small sizes of WDs, transits of Earth-sized and smaller planets orbiting them could easily be detected. As pointed out by Agol (2011), the habitable zone of a WD is close to its tidal disruption region. At the smallest possible separation, the probability for a transit is of course the highest, and Agol (2011) has outlined a survey for discovering such planets. Here we point out that, compared to planets transiting main-sequence stars, planets transiting WDs will also enjoy a much higher contrast of their atmospheric transmission signal above the background light of their host stars. This makes the characterization of a planet atmosphere via its transmission spectrum easily feasible with JWST. In particular, we show that the A absorption band of O$_2$ will be measurable, if O$_2$ is present in the exoplanet at the level found on Earth over the past 1 Gyr or so. Below, we calculate the parameters of the required WD survey, and the detectability of the sought-after atmospheric bio-signatures. We then simulate a JWST spectrum of an Earth-like planet transit across a WD, and summarize our main conclusions.

## 2 WHITE-DWARF SAMPLE REQUIREMENTS

We begin by estimating the size and type of the WD sample that would need to be assembled and surveyed, in order to discover a transiting Earth-like planet that would be amenable to an atmospheric bio-marker detection.

White dwarfs follow a narrow mass distribution, with most WDs at $M_{\text{wd}} \sim 0.6M_\odot$ (Kepler et al. 2007; Kleinman et al. 2013) or $M_{\text{wd}} \sim 0.65M_\odot$ (Holberg et al. 2008; Gianninas et al. 2011; Falcon et al. 2012; Giannichele et al. 2012). Either way, the radius of a WD of such typical mass is $R_{\text{wd}} \approx 8500$ km (e.g. Suh & Mathews 2000). Agol (2011) defines a “continuously habitable zone” around a WD that is habitable for at least 3 Gyr as a WD slowly cools. For an Earth-density planet orbiting an $M_{\text{wd}} = 0.6M_\odot$ WD, this zone extends from the tidal disruption limit, at semi-major axis $a \approx 0.005$ AU, out to $a \approx 0.02$ AU. Adopting $a = 0.01$AU as a fiducial value, the probability for a transit by a planet of radius $R_p$,

$$P_{\text{transit}} = \frac{(R_p + R_{\text{wd}})}{a}$$

obtains a value $P_{\text{transit}} = 0.01$ for an Earth-like planet with $R_p = 6400$ km. Supposing 20% of all WDs host an Earth in their continuously habitable zones, one would need to survey about 500 WDs to discover one transiting system.

Keeping an eye toward discovering the O$_2$ bio-marker in the planet transmission spectrum, and recalling that biogenerated O$_2$ appeared on Earth only after $\sim 2$ Gyr, we will focus on WDs that are $\sim 3$ Gyr old. Although this terracentric bias may be misguided, the limited available observational resources dictate that we focus on the systems most likely to have had enough time for oxygen-releasing life to evolve, rather than finding null results in systems
that have not had enough time. A 0.6\,M_\odot carbon-oxygen WD that cools for 3 Gyr reaches an effective temperature of T_{\text{eff}} \sim 6000\,K (Bergeron et al. 2001) and a bolometric absolute magnitude M_{bol} = 14.2. Apart from the fact that planets around such WDs will have resided in their continuous habitable zones already for a few Gyr, giving potential life some time to evolve, the temperature at this WD age can also be beneficial in terms of avoiding a hard UV spectrum that is likely detrimental to life forms.

Ignoring the subtle physics of WD cooling, the rate of change in the total thermal energy content of a WD equals the power that is thermally radiated away from its surface, \( L \propto T^4 \), and the thermal energy content is proportional to \( T \) (assuming a self-similar temperature profile throughout the cooling history). As a result, the cooling rate scales as

\[
\frac{dT}{dt} \propto T^4. \tag{2}
\]

The luminosity function of WDs that are born at a rate \( \frac{dN}{dt} \) will be

\[
\frac{dN}{dL} \propto \frac{dN}{dt} \frac{dT}{dL} \propto L^{-7/4}, \tag{3}
\]

with the last proportionality assuming a roughly constant star-formation rate, which leads to a constant WD formation rate, \( \frac{dN}{dt} = \text{const}. \) The number of WDs per logarithmic luminosity interval is then

\[
\frac{dN}{d(log L)} \propto L^{-3/4}. \tag{4}
\]

Harris et al. (2006) and Giammichele et al. (2012) derived consistent measurements of the luminosity function of local WDs, which is well fit by a power law with a sharp cutoff at \( M_{bol} \approx 15.4 \, \text{mag}. \) The logarithmic slope of their plotted WD luminosity functions appears remarkably similar to the expected \(-3/4\) value based on the above simple considerations. The cutoff magnitude, for a typical 0.6\,M_\odot WD, corresponds to a stellar life time of 2.5 Gyr plus a cooling time of 10 Gyr, that sum to about a Hubble time. At \( M_{bol} = 14.2 \, \text{mag}, \) the local density of WDs is \( 1.6 \times 10^{-3}\,\text{pc}^{-3}\,\text{mag}^{-1}. \) Assembling the brightest (and hence accessible to JWST spectroscopy) sample of 500 WDs with \( M_{bol} \sim 14.2 \, \text{mag} \) (that are therefore \sim 3 Gyr old) requires an all-sky survey for WDs that are within 40 pc. Most of the WDs in the sample will thus have an apparent magnitude of \sim 17.2. While such an all-sky sample of local WDs does not exist as of yet, the upcoming \textit{Gaia}\textsuperscript{4} astrometric mission, which will have errors of < 0.1 milliarcsec at this magnitude, will easily detect the trigonometric parallaxes of such WDs and will permit assembling a WD sample such as this.

The WD sample will then need to be monitored photometrically, to find the one or two cases, if they exist, that are transited by habitable-zone Earth-size planets. As noted by Agol (2011), about 10% of any existing transiting planets around these WDs will be discovered already in \textit{Gaia} photometry, so there is a mild chance to find a transiting earth already at that stage. The orbital period will be of order 10 to 20 hours, and the transit will last of order a minute or two, during which the WD flux will decrease by order unity. The surveying stage can thus be carried out with a number of dedicated, 0.5m-class, telescopes, that monitor each WD continuously with 1-min cadences for a night or two. The candidate transiting cases can be followed up, using larger telescopes, with shorter-cadence photometry and radial-velocity spectroscopic observations, to determine transit ephemerides, planet sizes, and masses.

3 BIO-MARKER DETECTION REQUIREMENTS

If and when an Earth-like planet transiting a WD has been discovered, its atmosphere can be characterized via transmission spectroscopy. When observing a continuum source through one radial column of the Earth’s atmosphere at resolutions \( R \gtrsim 20,000, \) the optical O\(_2\) lines become resolved and reach centre-line depths of \sim 100\% in the A band and \sim 50\% in the B band (and considerably weaker in the \gamma band, which we will not consider further). At a resolution of \( R \sim 700 \) that is practical with JWST in this case, the line depths are reduced by factors of a few.

Because an Earth-like planet and a WD are of comparable size, the planet will cover about one-half of the WD disk during a typical transit. The area of the WD that is covered by the planet atmosphere will then be about 2\( \pi R_p n H / 3 \), where \( H \) is the exponential scale height of the planet atmosphere, and \( n H \) is the height above the planet surface at which a line of sight tangent to the planet passes a column of atmosphere equal to one vertical column. This requirement on \( n \) can be approximated as

\[
e^{-3/2} 2\sqrt{n R_p / H} \approx 1. \tag{5}
\]

A planet’s radius \( R_p \) depends on the planet mass and composition. The atmospheric scale height \( H \) will depend on the gravitational acceleration at the planet’s surface \( g \), and thus again on the planet’s mass and composition, but also on the atmospheric composition and temperature \( T_{\text{atm}} \).

\[
H = \frac{k_p T_{\text{atm}}}{\mu g} = \frac{c_s^2}{g}, \tag{6}
\]

where \( k_p \) is the Boltzmann constant, \( \mu \) is the mean molecular mass, and \( c_s \equiv (k_p T_{\text{atm}} / \mu)^{1/2} \) is the sound speed. \( T_{\text{atm}} \), in turn, depends on atmospheric composition and distance from the parent star. Thus, planets of differing masses, compositions, and orbits will have different ratios \( R_p / H \), and hence differing values of \( n \) that satisfy the transcendental equation \ref{eq:5}. Nevertheless, for a range of real planet \( R_p / H \) ratios, \( n \) equals approximately 5. We find that for the Earth, with \( R_p = 6400 \, \text{km} \) and \( H = 10 \, \text{km}, \) \( n \approx 4.7 \). For Jupiter, with \( R_p = 70,000 \, \text{km} \) and \( H = 27 \, \text{km}, \) \( n \approx 5.5 \). For a hot Jupiter, with \( T_{\text{atm}} \) that is 5 times higher than Jupiter’s, \( n \approx 4.6 \). Beckwith (2008) has solved the integral expression for the atmospheric path length giving \( n \), and derived \( n = 4.2 \) for terrestrial parameters.

The unocculted area of the WD will typically be \( \pi R_{\text{wd}}^2 / 2 \), because for the average transit impact parameter roughly one-half of the WD area will be covered by the planet. The contrast between the atmospheric signal \( S \) (which we define here as the part of the WD light that impinges upon the atmospheric annulus) and the unocculted background \( B \) is then:

\[
\frac{S}{B} \approx \frac{4 n H R_p}{3 R_{\text{wd}}^2} \approx \frac{1}{170}. \tag{7}
\]
for an Earth-like planet transiting a WD. This is of course a much larger and more favourable contrast ratio than in the case of earths transiting main-sequence stars. The dominant source of noise involves Poisson fluctuations in the number of photons from the unobscured light of the background star, in this case the WD. The required number of detected signal photons in the transmitted spectrum, for a given $S/N$, therefore satisfies

$$\frac{S}{\sqrt{170S}} = S/N,$$

or $S \approx 4000$ signal photons and $B \approx 7 \times 10^3$ background photons per spectral resolution element for $S/N = 5$. In §4 we show that such a $S/N$ in the continuum of the transmitted spectrum is sufficient for detecting clearly the $O_2$ A-band absorption, which at $R \sim 700$ has a band-center absorption depth of about 50%, and spans several resolution elements.

The half-occulted WD will have about 18 mag, and hence a photon flux of $f_{ph} \sim 8 \times 10^{-5} \text{s}^{-1} \text{cm}^{-2} \text{Å}^{-1}$ at a wavelength of $\sim 7000$ Å. For JWST, 0.88 of the 6.5-meter-diameter collecting area is unobstructed, and for the Near Infrared Imaging Slitless Spectrograph (NIRISS) with the GR700XD grism ($R \sim 700$) the total system throughput at $\sim 7000$ Å is about 0.15 (Doyon 2012). During a single transit of length of 2 minutes, about 4,200 photons per 10 Å resolution element will be accumulated. Integrating over 160 such 2-minute transits, the required $S/N$ for detecting the oxygen bands will be obtained. This would amount to 5.3 hours of net JWST exposure time (i.e. excluding telescope overheads), albeit spread out over daily or twice-daily visits during several months.

If the exoplanet atmosphere has an $O_2$ abundance of only a few percent, i.e. 1/10 of the present level, as was on Earth at ages $\sim 2$–$3.5$ Gyr, the $O_2$ signature will be undetectable, unless one resorts to JWST exposures which are 100 times longer (as are being considered for studying planets around M stars). On the other hand, the near-infrared spectrum will be obtained simultaneously in the full $0.6–2.5$ µm NIRISS wavelength range, over which the system throughput is 30–40%. Strong signatures of other molecular species in the the planet atmosphere, such as water and CO$_2$, will be detectable with < 1 hr exposure.

Naturally, if a suitable habitable-zone Earth-mass planet transiting a WD is discovered at the survey stage, it will be straightforward to obtain its atmospheric transmission spectrum with a ground-based 10-m-class telescope, if the planet atmosphere is significantly different from the terrestrial example. With a collecting area 3 times larger than JWST, the total exposure time would be correspondingly shortened. The added challenge of variable telluric atmospheric absorption during and out of transit could be addressed by simultaneously observing, through the instrument slit, a neighbouring star of similar brightness. However, if the planet atmosphere is also Earth-like, it will be difficult to detect it from the ground, after our own highly variable (both temporally and spatially) atmosphere has imprinted on the spectrum the same signature, but $\sim 170$ times stronger. Indeed, a null ground-based detection of a planetary atmosphere could mean either that there is no planet atmosphere or that there is one but it is similar to Earth’s, hence requiring a space-based telescope such as JWST. Alternatively, Snellen et al. (2013) have described a program for detecting the atmosphere of an Earth twin utilising the next generation of large telescopes and very high spectral resolution, to separate the extraterrestrial and telluric signals by means of the velocity shift of the planet lines.

For planets larger than the WD, which will typically occult the WD completely during transit, the probability of a transit of the planet atmosphere across the WD will be

$$P_{\text{transit-\text{atm}}} = \frac{2R_{\text{wd}}}{\pi a},$$

i.e., similar to the Earth-like case. However, given that the planet temperature will be the same as in the previous Earth-size case (assuming $a$ in the habitable zone), but the gravity will be larger in proportion to $R_p$, the scale height $H$ will be proportionally smaller. The area covered by the planet atmosphere will be typically just $R_{\text{atm}}H$. For planets larger than the WD, the atmospheric transmission signal will thus decrease linearly with planet radius, while the background emission from the WD will remain unchanged, and hence the required exposure times will increase in proportion to the planet radius. Among planets transiting WDs, Earth-like planets are thus optimal for atmospheric transmission studies, since their radius is similar to that of WDs.

### 4 SPECTRAL SIMULATION

To demonstrate the feasibility of the proposed observations, we have simulated the JWST transmission spectrum observation of an Earth-like planet transiting a WD in the $0.6–2.5$ µm wavelength range. The Earth’s empirical atmospheric absorption spectrum, including the optical $O_2$ bands at $\sim 6000$ – $8000$ Å, was taken from Wallace et al. (2011) based on observations of the Sun at different air masses. For the wavelength band of $0.9–2.5$ µm, we use the infrared atmospheric transmission spectra available at the Gemini Ob-
region dominated by strong absorption features of H$_2$O and CO$_2$. The H$_2$O feature would be visible also in an exposure shorter by a factor of 10.

The amount of water vapour one could expect to observe in transmission in any Earth-like planet, let alone in a planet orbiting a WD, is highly uncertain. On the one hand, the terrestrial mean water column is 25 mm, i.e. 15 times larger than what we have adopted. On the other hand, almost all of the terrestrial water vapour is confined within one scale height, i.e. within a projected atmospheric area that is 5 times smaller than what we have assumed. But then, most or all of this water-vapour-rich atmospheric layer could be hidden from view in an exoplanet transmission spectrum by optically thick clouds or haze of water (e.g. Burgasser 2009). The uncertainties associated with the existence and height of clouds as well as the composition and mixing of the atmosphere, can lead to a very broad range of possible H$_2$O absorption strengths in an exoplanet atmosphere (e.g. Fujii et al. 2012). The 1.6 mm column we have chosen to illustrate the effect is therefore just one of many possible values. Refraction in the planet atmosphere is another factor that could affect the expected signal (Garcia-Munoz et al. 2012).

We have rebinned the full 0.6 – 2.5 μm absorption spectrum to the R ~ 700 spectral resolution of the NIRISS GR700XD grism, diluted it with the WD continuum emission (170 times brighter) and added Poisson noise according to the total expected photon counts, as described in § 3. This procedure implicitly assumes that the transmission spectrum through a height nH is representative of the spectrum at all heights, from zero to to nH above the surface of the planet. In reality, for a tangential path below about 10 km, the Earth’s atmosphere becomes quite opaque at most wavelengths, due to absorption by ozone bands, in addition to water clouds, aerosols, and Rayleigh scattering, and therefore these lowest regions will not contribute to the transmission signal. On the other hand, at intermediate heights, the interesting absorbers actually have a larger optical depth, and hence layers at those heights contribute a stronger signal, than those at nH (see Kaltenegger & Traub 2009). In the balance, the above assumption provides a reasonable approximation of the expected spectrum.

Figures 1 and 2 show representative spectral regions of the simulated spectrum in the optical band around the O$_2$ A and B bands and in the infrared region around several H$_2$O and CO$_2$ features. The O$_2$ A-band and the H$_2$O and CO$_2$ features are all clearly detected in this simulated 5.3 hr integrated exposure. We have verified that the H$_2$O band, which is strong and broad, is detectable even with 10% of the exposure time.

5 CONCLUSIONS

We have shown that JWST will be able to detect the O$_2$ biosignature in the absorption spectrum of a habitable Earth-mass planet as it transits a WD, after a total integration time of about 5 hours. Finding a suitable planetary system requires first assembling a sample of ~ 500 WDs with apparent magnitudes of ~ 17 within ~ 40 pc, which is feasible with Gaia, and then monitoring them with small telescopes in order to find the transits. Earth-mass planets in the habitable zones of WDs may offer the best prospects for detecting bio-signatures within the coming decade.

ACKNOWLEDGMENTS

We thank Mukremin Kilic, Remko de Kok, Tsevi Mazeh, Dimitar Sasselov, Laura Schaefer, Ignas Snellen, Dave Spiegel, Amiel Sternberg, Lev Tal-Or, and the anonymous referee, for useful input. A. L. acknowledges support from the Sackler Professorship by Special Appointment at Tel Aviv University, which enabled this collaboration. D.M acknowledges support by a grant from the US-Israel Binational Science Foundation.

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