Solar Abundances of Rock Forming Elements, Extreme Oxygen and Hydrogen in a Young Polluted White Dwarf

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ABSTRACT
The $T_{\text{eff}} = 20800 \text{ K}$ white dwarf WD 1536$+520$ is shown to have broadly solar abundances of the major rock forming elements O, Mg, Al, Si, Ca, and Fe, together with a strong relative depletion in the volatile elements C and S. In addition to the highest metal abundances observed to date, including log (O/He) $= -3.4$, the helium-dominated atmosphere has an exceptional hydrogen abundance at log (H/He) $= -1.7$. Within the uncertainties, the metal-to-metal ratios are consistent with the accretion of an H$_2$O-rich and rocky parent body, an interpretation supported by the anomalously high trace hydrogen. The mixed atmosphere yields unusually short diffusion timescales for a helium atmosphere white dwarf, of no more than a few hundred yr, and equivalent to those in a much cooler, hydrogen-rich star. The overall heavy element abundances of the disrupted parent body deviate modestly from a bulk Earth pattern, and suggest the deposition of some core-like material. The total inferred accretion rate is $4.2 \times 10^9 \text{ g s}^{-1}$, and at least 4 times higher than any white dwarf with a comparable diffusion timescale. Notably, when accretion is exhausted in this system, both metals and hydrogen will become undetectable within roughly 300 Myr, thus supporting a scenario where the trace hydrogen is related to the ongoing accretion of planetary debris.

Key words: circumstellar matter— stars: abundances— stars: individual (WD 1536$+520$)— planetary systems— white dwarfs

1 INTRODUCTION
A decade of observational and theoretical studies by many astronomers has shown, that over a wide range of effective stellar temperatures, the presence of heavy elements in white dwarf atmospheres is evidence for orbiting planetary systems (Farihi et al. 2014; Vanderburg et al. 2015; Jura & Young 2014; Veras et al. 2015). With this relatively recent shift in paradigm, the discovery of the prototype, metal-lined white dwarf by van Maanen (1917) nearly a century ago – while not a planet detection itself, but the signature of accreted planetary debris – is arguably the first astronomical evidence of the presence of planetary systems around other stars (Zuckerman 2015).

According to all dynamical models that deliver sufficient planetesimal masses into the innermost system where it can be accreted, each exoplanetary system hosted by a metal-enriched white dwarf must harbor at least a belt of minor bodies and one major planet (Frewen & Hansen 2014; Veras et al. 2013; Debes et al. 2012; Bonsor et al. 2011). The gravitational field of the planet(s) can perturb the orbits of the planetesimals onto orbits passing near the white dwarf so that they are tidally disrupted. Spitzer and complementary ground-based observations have established a firm connection between the atmospheric heavy elements in white dwarfs and the presence of dust and gas within the tidal radius of the star (Farihi et al. 2009; von Hippel et al. 2007; Jura et al. 2007; Gänscicke et al. 2006).

Because the metal-to-metal sinking timescales vary by no more than a factor of a few, the relative, steady-state abundances of the accreted planetary debris can be analytically linked to those observed in the polluted atmosphere (Koester 2009), thus making the stellar surface an effective mirror of planetesimal composition. The first detailed abundance study of any metal-enriched white dwarf was carried out for the current record holder for number (16) of detected heavy elements, GD 362, demonstrating that the debris was broadly terrestrial-like (Zuckerman et al. 2007). Since then, the broad pattern of bulk, Earth-like compositions has been seen – especially with ultraviolet HST observations – in several more stars.
with five or more heavy elements (O, Mg, Si, Ca, Fe) that indicate melting and differentiation among extrasolar, rocky planetesimals, and a diversity of overall compositions similar to different classes of Solar System meteorites (Xu et al. 2013; Gänzicke et al. 2012).

Importantly, while most polluted white dwarfs appear to be contaminated by debris from parent bodies that were relatively poor in H2O and other volatiles (Jura & Xu 2012), there is at least one case where substantial H2O can be confirmed in an otherwise volatile- and carbon-poor planetesimal. The debris orbiting and polluting the atmosphere of GD 61 originated in a rocky minor planet roughly the size of Vesta and containing approximately 26% water by mass (Farhi et al. 2013). Another polluted white dwarf with a substantial oxygen excess is SDSS J124231.07+522626.6, where the parent body likely had an even higher water content (Raddi et al. 2015). Such water-rich asteroids are important as potential building blocks of habitable planetary surfaces, especially if most small and rocky planets form dry as did the Earth (Morbidelli et al. 2000).

This paper reports the identification and analysis of H, O, Mg, Al, Si, Ca, Ti, Cr, and Fe in the helium atmosphere white dwarf WD 1536+520. These elements are found to be accreting at a rate higher than any yet measured in a white dwarf with relatively short sinking timescales, and producing atmospheric metal abundances comparable to those of the Sun. The data are consistent with a refractory-rich parent body with a modest fraction of H2O. Section 2 presents spectroscopic observations from several facilities that resulted in the detection of all the major rock forming elements, and strong upper limits on key volatiles. The atmospheric modeling is discussed in Section 3, along with the determination of stellar parameters, and elemental abundances within the star and the disrupted parent body. The paper explores the so-far unique properties of this star as something of a transition object between helium- and hydrogen-rich, polluted white dwarfs, with the conclusions presented in Section 4.

2 OBSERVATIONS

WD 1536+520 was first identified in the Second Byurakan Sky Survey (SBS 1536+520; Stepanian et al. 1992; Balvan 1997) in 1992 and correctly typed as a DBA (strongest lines He I, weaker lines of H) white dwarf from a low resolution, R ≈ 400 spectrum. It was spectroscopically observed as part the Sloan Digital Sky Survey in 2002 (SDSS 153725.71+515126.9; Eisenstein et al. 2006), and exhibits lines of Mg, Si, and Ca in these R ≈ 2000 data (Gänzicke et al. 2016), yielding a full spectral type of DBAZ. Given that the SDSS ugriz photometry alone results in a temperature estimate of 22,000 K (Girven et al. 2011), the presence of these metal absorption features in a modest resolution spectrum is remarkable – at similar T_eff and irrespective of atmospheric composition, the detection of atmospheric metals in white dwarfs typically requires powerful, high-resolution spectroscopy with Keck or the VLT (Koester et al. 2008). The star has an infrared excess detected byWISE (Debes et al. 2011; Barber et al. 2014) at 3.4 and 4.6 μm, where the data are consistent with passively heated debris orbiting within the Roche limit, similar to roughly 40 other metal-enriched white dwarfs accreting from analogous disks (Farhi 2016).

Follow up observations were obtained in 2014 April with the MMT using the Blue Channel Spectrograph. Spectra were taken through a 16 slit with the 832 l mm⁻¹ grating in first and second order, covering 6200 – 8100 Å at 2 Å resolution and 3200 – 4100 Å at 1 Å resolution respectively. The red spectrum consisted of four 900 s exposures in clear conditions, while the blue spectrum comprised three 600 s exposures but intruding on twilight where significant sky signal was present. The blue data are thus of relatively modest quality, while the red spectra are superior and a combined spectrum is shown in Figure 1. Most important, these modest resolution data exhibit a strong O I 7775 Å absorption feature, in addition to lines of Mg II, and Si II.

Additional, medium-resolution spectra were taken in 2014 July using the double arm ISIS spectrograph on the WHT. Simultaneous blue and red spectra were taken through a 16 slit using the R1200B and R1200R gratings, with the 5300 Å dichroic, resulting in two spectra covering 4500 – 6000 Å at a resolution of roughly 1 Å. The white dwarf was observed continuously for eight exposures of 900 s in good conditions. The ISIS spectra reveal weak Al II and Si II features in wavelength regions not covered by the MMT dataset.

Lastly, high-resolution observations carried out in 2015 April with the HIRESb spectrograph on Keck I. The setup was identi-
3 Atmospheric Parameters and Abundance Patterns

The multiple spectral datasets were analyzed together using white dwarf atmospheric models, where the input physics is detailed in Koester (2010). The final stellar parameters were based on spectral fits to the latest SDSS spectrum, obtained with the BOSS spectrograph. We calculated a 3-dimensional model grid in $T_{\text{eff}}$, log g, and [H/He], keeping the latter fixed while fitting the first two parameters. This is a more stable procedure than fitting for all three parameters, since the effect of [He/H] and log g on the spectrum is much smaller than that of the temperature. The results indicate the best fit is near 20,800 K, which was confirmed by repeating a similar fit with log g kept fixed and fitting for $T_{\text{eff}}$ and [H/He]. The final stellar parameters are given in Table 1.

For the determination of abundances and upper limits, all available spectra (Keck, MMT, SDSS, WHT) were used with the method of line profile fitting. Table 2 lists all the individual ions and wavelengths used for this purpose. After a good fit was approximated, models were re-calculated with $\pm0.3$ dex abundances, which is much smaller than that of the temperature. The results indicate the best fit is near 20,800 K, which was confirmed by repeating a similar fit with log g kept fixed and fitting for $T_{\text{eff}}$ and [H/He]. The final stellar parameters are given in Table 1.

where visual inspection of each line determined the abundance and an error estimate. In the case of multiple lines the final abundance was determined as a weighted average. Repeating the analysis with $T_{\text{eff}}$ and log g varied within the adopted errors, the systematic errors found were to be approximately 0.20 dex, but in the same direction for all elements. Relative abundance errors are 0.05 dex. The changes of the convection zone and diffusion timescales contribute 0.10 dex; and thus the total systematic error in relative abundances is 0.12 dex.

3.1 Bulk Composition of Accreted Debris

The abundances, relative to helium, of all trace elements are given Table 3 together with diffusion timescales for each species. The third column compares the atmospheric, heavy element abundances in the white dwarf (relative to He) in units of solar values (relative to H; Lodders 2003), demonstrating that WD 1536 nominally exceeds the solar values for nearly all detected elements. These absolute abundances surpass the previous record holder SDSS J073842.56+183509.6 (Dufour et al. 2010) by a factor of 3–10, and GD 362 by over an order of magnitude (Xu et al. 2013).

Also calculated are the mass of each element present in the photosphere of the star, which is equivalent to the mass fraction of a given element $X_{\text{z}}$, multiplied by the mass of the convection zone $M_{\text{z\text{conv}}}$. If WD 1536 is in an early phase of accretion, where less than a single diffusion timescale has expired since the onset of atmospheric pollution, then the metal-to-metal abundances of the infalling debris are exactly mirrored by those in the atmosphere and given in the fifth column. If instead pollution has been ongoing for at least 5 diffusion timescales (Koester 2009), then the system is in a steady-state balance between accretion and diffusion and the abundance ratios are reflected in the sixth column. For all detected
elements but oxygen, the metal-to-metal ratios show little variation between the early phase and steady state solutions.

In Figure 2 are plotted both the early phase and steady state abundances of heavy elements, relative to silicon and normalized to the bulk Earth values from Allègre et al. (2001). As can be seen, the debris orbiting and polluting WD 1536 is bulk Earth-like in the major rock forming elements to within a factor of around two. There is a notable enhancement in chromium, yet an apparent deficit in phosphorus. This two-fold deviation in opposite directions is difficult to reconcile, as both chromium and phosphorus are siderophiles with similar condensation temperatures (Lodders 2003). Similar enhancements in chromium have been seen in the white dwarfs PG 0843+516 and GALEX J193156.8+011745 (Gänścieke et al. 2012) – together with bulk Earth or higher phosphorous abundances, as expected – but are otherwise not commonly seen in polluted white dwarfs (Xu et al. 2014; Jura et al. 2012). Because phosphorus has only been detected in white dwarfs at ultraviolet wavelengths, the upper limit derived for WD 1536 from optical data may be uncertain. With this caveat, the data are consistent with the accretion of substantial core-like material.

3.2 Oxygen Excess and Hydrogen Accreted from H2O

The total oxygen budget can be evaluated by accounting for all the expected oxides originating in planetary solids (Farhi et al. 2013b; Klein et al. 2014). In the early phase and steady state scenarios, oxygen is first assumed to be carried exclusively by MgO, Al2O3, SiO2, CaO, and FeO within the debris. There are three possible outcomes from such an analysis.

(i) Insufficient oxygen to account for metal oxides. This outcome can imply that iron was delivered not as FeO but substantially as metal.

Table 4. Oxide, Iron Metal, and Water Mass Fractions

| Oxygen Carrier | Early Phase | Steady State |
|----------------|-------------|--------------|
| MgO            | 0.22        | 0.40         |
| Al2O3          | 0.02        | 0.03         |
| SiO2           | 0.24        | 0.59         |
| CaO            | 0.01        | 0.03         |
| FeO            | 0.08        | 0.00         |

Excess oxygen beyond that of anhydrous minerals alone. In this case, H2O is the most likely source of the oxygen surplus.

Carbon can confidently be ignored as an oxygen carrier for the following reasons. First, carbon has been found to be significantly depleted relative to solar and volatile-rich, cometary abundance patterns in nearly all polluted white dwarfs where measurements are available (Wilson et al. 2016; Koester et al. 2014; Farhi et al. 2013a; Jura et al. 2012; Gänścieke et al. 2012; Jura 2006). Second, CO and CO2 are no more than 5%–10% of the volatile content of Solar System comets, which are dominated by water ice (Binzel et al. 2000). Third, for WD 1536 in particular, the upper limit carbon abundance suggests that it cannot be a significant source of excess oxygen.

Table 4 evaluates the nominal oxygen budget for WD 1536 for both an early phase and steady state accretion history. In the steady state, there is insufficient oxygen to account for Mg, Al, Si, Ca, and Fe bound in oxides – only if 100% of the iron was delivered as metal or alloy can the oxygen budget be considered balanced and physical. In this case, the nominal oxygen abundance still requires a modest, 5–10% increase to account for the other elements (Mg, Al, Si, Ca) that only form rocks, but such leeway is well within the uncertainties. This is another strong indication that the material orbiting and polluting the white dwarf has a substantial core-like component. Of the total iron mass present in the Earth, metallic Fe in the core is thought to represent 87%, whereas Fe in the mantle and crust is only 13% (McDonough 2000), some of which is also metal. Thus, the scenario where the iron in WD 1536 was contained essentially in pure metals or alloys is plausible. Within the derived photospheric abundance errors, a steady state solution without any iron oxides would readily allow for solutions where the parent body contained water ice or hydrated minerals.

While the range of allowed abundance ratios also permits solutions without any excess oxygen, the striking hydrogen abundance in WD 1536 must be considered, and which clearly favors a water-rich interpretation. While an early phase of accretion predicts an oxygen excess and thus the need for H2O within the planetary debris, the heavy element settling times are relatively short, and thus...
with updated diffusion data (http://www1.astrophysik.uni-kiel.de/ based solely on Ca, following the method outlined in Farihi et al. (2012) (Bergfors et al. 2014). For consistency, all plotted rates and timescales are a large sample of metal-enriched white dwarfs observed with Figure 3. accretion rates and sinking timescales based on CaII detections (Bergfors et al. 2014). WD 1536 lies above threehydrogen-rich stars whose disks have been detected in the in-

Figure 3. Accretion rate versus diffusion timescale for WD 1536 and a large sample of metal-enriched white dwarfs observed with Spitzer (Bergfors et al. 2014). For consistency, all plotted rates and timescales are based solely on Ca, following the method outlined in Farihi et al. (2013) with updated diffusion data (http://www1.astrophysik.uni-kiel.de/~koester; Koester 2009). The hydrogen-rich stars are shown as red filled and black open circles, while the helium-rich stars are shown as blue filled and grey open circles; filled symbols correspond to the detection of infrared excess. Within each atmospheric class, left to right represents decreasing $T_{\text{eff}}$. Remarkably, WD 1536 sits in a region that is otherwise exclusively occupied by stars with hydrogen atmospheres. G166-58 is the coolest white dwarf with a hydrogen-rich atmosphere and an infrared excess.

catching the star in this phase is less likely. If disks last for at least $10^5$ yr (Girven et al. 2012), then the probability that WD 1536 is not yet in a steady-state phase of accretion is less than 1%. The total hydrogen mass within the stellar atmosphere is $4.0 \times 10^{19}$ g, and could have been delivered by an asteroid with total mass a few to several times $10^{21}$ g and which was 5–10% H$_2$O by mass. This would be consistent with the lower mass limit of $4.2 \times 10^{19}$ g from the heavy elements alone.

While uncertain, the totality of data discussed in this section favors the deposition of H$_2$O onto the stellar surface and carried by the parent body whose debris now orbits the star. In the next section, the anomalously high trace hydrogen abundance is shown to be transient, thus strengthening this interpretation.

3.3 Anomalous Diffusion Timescales and Trace H

The mass of the convection zone in WD 1536 is tiny – $10^6$ times smaller than those within the bulk of known polluted white dwarfs with helium atmospheres. There are two reasons for this. First, the $T_{\text{eff}}$ and 60 Myr cooling age mean the star is experiencing the early stages of convection zone growth (Paquette et al. 1986). In fact, with $T_{\text{eff}} > 20000$ K this star is the warmest and youngest helium-rich white dwarf to show metals due to ongoing accretion. Second, the anomalously high fraction of hydrogen leads to a significant reduction in the depth of the outer layers relative to a pure helium composition, by a factor of approximately 30.

These facts conspire to make the stellar atmosphere physically similar to a typical 10,000 K hydrogen-rich white dwarf, with comparable diffusion timescales. Figure 3 plots WD 1536 together with a sample of polluted white dwarfs observed with Spitzer, as a function of their inferred accretion rates and sinking timescales based on CaII detections (Bergfors et al. 2014). WD 1536 lies above three hydrogen-rich stars whose disks have been detected in the inner regions of planetesimals towards the white dwarf host, consistent with theoretical predictions (Mustill et al. 2014; Veras et al. 2013).

Figure 4 highlights the exceptional H/He in WD 1536. The upper panel plots samples of helium-rich white dwarfs with trace hydrogen detected directly through Balmer absorption features (typi-
Interestingly, a substantial fraction of the plotted stars are also polluted with heavy elements, although a strong bias is present at $T_{\text{eff}} \lesssim 12000$ K. In this cooler temperature range, He absorption rapidly becomes too weak to detect in low- and medium-resolution spectra, whereas strong Ca II absorption can indicate a helium-rich atmosphere (Dufour et al. 2007). At the warmer end of the temperatures shown in Figure 4, the bias towards metal detection is not an issue. Caution should be used when viewing Figure 4; the plotted stars do not represent an evolutionary sequence, and selection biases play a large role. That being said, the cooler stars with substantial hydrogen are either born with substantially more massive reservoirs than can currently be inferred in earlier evolutionary stages, or accrete H-rich planetary material.

### 3.4 H/He Evolution

Assuming complete mixing of the outer stellar layers, the lower panel of Fig. 4 plots tracks of constant hydrogen mass within otherwise-pure helium atmosphere white dwarfs, as a function of temperature (Koester 2009). In this simple model where no stratification occurs between hydrogen and helium, the observational signature of most fixed masses of hydrogen at $T_{\text{eff}} \approx 20000$ K will gradually disappear from white dwarfs with helium-dominated atmospheres. The fact that some stars retain (or re-gain) substantial hydrogen masses at later times, is a well-known problem in white dwarf atmospheric evolution (MacDonald & Venne 1991). While this general topic is beyond the scope of this paper, two distinct possibilities are 1) hydrogen is accreted over long timescales, or 2) primordial hydrogen floats over a deeper helium reservoir, and is later mixed into the photosphere. In the latter scenario, stars will appear hydrogen-rich at sufficiently warm temperatures and later reveal themselves to be helium-dominated (Bergeron et al. 2011; Fontaine & Wesemael 1987). Currently, there is more observational support for the primordial model, with at least 3/4 of helium atmosphere white dwarfs showing traces of hydrogen (Koester & Kepler 2015).

Thus in the absence of continued accretion WD 1536 will have both its metals and trace hydrogen wiped clean from its photosphere. Without the influence of ongoing, external pollution, the heavy elements will completely sink beneath the photosphere within a few $10^3$ years at most. But over longer timescales, the remarkably high abundance of atmospheric hydrogen will be drowned by the deepening helium convection zone. By the time WD 1536 has cooled to 15 000 K in 140 Myr, the mass of the convection zone will have grown by 4 orders of magnitude and exhibit a trace hydrogen abundance $\log$(H/He) $\approx -5.7$. At this stage, the star will either appear as a fairly average helium-rich white dwarf, where hydrogen is difficult or impossible to detect in modest resolution spectra due to its apparent faintness relative to the nearby samples shown in Fig 4. When the star has cooled to 12 000 K after another 190 Myr, it will certainly not have detectable hydrogen. The unavoidable conclusion is that this white dwarf is being witnessed at a special time, in a transient phase, and the hydrogen is related to the orbiting planetary debris, and thus water is likely present.

Considering that WD 1536 may have only accreted $\sim 10^{19}$ g of hydrogen onto its atmosphere and $\log$(H/He) $\approx -1.7$, it can be seen that if a significantly larger and water-rich parent body had been deposited, then hydrogen could (temporarily) have become the dominant atmospheric constituent. For example, the disrupted asteroids polluting GD 61 or SDSS 1242 might have delivered $\sim 10^{21}$ g or $\sim 10^{25}$ g of hydrogen respectively, resulting in abundances of $\log$(H/He) $\approx 0$ and $\log$(H/He) $\approx +2$. In both cases WD 1536 would temporarily appear as a hydrogen-rich star despite being dominated by the underlying helium. Therefore, the accretion of water-rich planetary debris has the potential to have an observable effect on H/He white dwarf spectral evolution.

### 4 CONCLUSION

The young, helium-atmosphere, white dwarf WD 1536 exhibits the highest abundances of heavy elements yet seen among polluted hosts of evolved planetary systems. In addition to the broadly solar abundances of the major rock forming elements O, Mg, Al, Si, Ca, and Fe, this star also has a remarkably high trace hydrogen abundance $\log$(H/He) $\approx -1.7$. Considering the 1) abundance pattern of heavy elements, 2) the anomalously high trace hydrogen, and 3) the transient detectability of both the metals and the hydrogen, the most realistic conclusion is that the parent body whose debris is both orbiting and polluting WD 1536 contained traces of H$_2$O.

The thinness of the convection zone is a result of relative youth and relatively high mass of trace hydrogen within a helium-dominated atmosphere. Due to these combined facts, the outer layers of WD 1536 essentially behave as a hydrogen-rich white dwarf, with metal sinking timescales of only a few hundred years at most, hence supporting a steady state interpretation of the metal abundances. If these are indeed in a steady state, then WD 1536 has the highest instantaneous accretion rate yet observed among polluted white dwarfs.

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