ABSTRACT

Between 30 - 50% of white dwarfs (WDs) show heavy elements in their atmospheres. This “pollution” is thought to arise from the accretion of planetesimals perturbed by outer planet(s) to within the WD’s tidal disruption radius. A small fraction of these WDs show either emission or absorption from circumstellar (C-S) gas. The abundances of metals in the photospheres of WDs with C-S gas are mostly similar to the bulk composition of the Earth. The C-S component arises from gas produced through collisions and/or the sublimation of disintegrating planetesimals. High resolution spectroscopic observations of WD 1124-293 reveal photospheric and C-S absorption of Ca in multiple transitions. Here, we present high signal-to-noise ratio spectra, an updated WD atmosphere analysis, and a self-consistent model of its C-S gas. We constrain the abundances of Ca, Mg, and Fe in the photosphere of WD 1124-293, and find agreement with the abundances of these 3 species in the C-S gas. We find the location of the C-S gas is about a hundred white dwarf radii, the C-S and photospheric compositions are thus far consistent, the gas is not isothermal, and the amount of C-S Ca has not changed in two decades. We also demonstrate how to use Cloudy to model C-S gas viewed in absorption around polluted WDs. Modeling the abundances of C-S gas around polluted WDs with Cloudy provides a new method to measure the composition of exo-planetesimals and will allow a direct comparison to the composition of rocky bodies in the Solar System.

Keywords: DA stars (348), DB stars (358), Circumstellar gas(238), Circumstellar matter(241)

1. INTRODUCTION

The spectra of white dwarfs (WDs) should show only pressure-broadened hydrogen and/or helium absorption lines, yet at least 27% of young WDs with temperatures less than ~27,000 K have photospheres polluted by elements heavier than helium (Koester et al. 2014). These metals should settle out of the atmospheres of WDs on timescales of days to Myr depending on the WD temperature, surface gravity, and main atmospheric composition (H vs. He) (Koester 2009). For isolated WDs, the pollution could arise from grains in the interstellar medium (ISM) (Dupuis et al. 1993a,b), or more likely, from the accretion of solids that have been liberated from a captured planetesimal (e.g. WD 1145+017l Vanderburg et al. 2015). The gas phase of the latter accretion process can exist as a circumstellar disk observable as a double peaked line in emission (e.g. Manser et al. 2016) or a Doppler broadened profile in absorption (e.g. Xu et al. 2016). WD 1124-293 is one of a few WDs that shows both metal photospheric absorption and circumstellar absorption features.

We investigate the gas toward WD 1124-293 to explore the conditions necessary to produce the observed absorption. WD 1124-293 is of spectral type DAZ (a hydrogen dominated atmosphere with metal lines), has an effective temperature $T_{\text{eff}} \sim 9367$K, and surface gravity log $g = 7.99$ (see Table 1). The one observed C-S Ca K absorption feature detected at 8σ (Debes et al. 2012) provides an opportunity to explore the physical conditions that result in this type of spectrum. We use the microphysics code, Cloudy, to model the metal-rich gas polluting WD 1124-293 by creating a grid of models of C-S gas to explore the abundances of elements from He to Zn relative to hydrogen. Due to the lack of an infrared
Table 1. Properties of WD 1124-293

| Parameter            | Value       | Reference |
|----------------------|-------------|-----------|
| RA, Dec (J2000)      | 11:27:09.25, ~29:40:11.20 | a         |
| Spectral Type        | DAZ         | b         |
| G (mag)              | 15.0139     | a         |
| $T_{wd}$ (K)         | 9367        | c         |
| log $g$ (cm s$^{-2}$) | 7.99        | c         |
| $R_{wd}$ ($R_\odot$) | 0.0127      | c         |
| $M_{wd}$ ($M_\odot$) | 0.575       | c         |
| Luminosity ($L_\odot$) | 0.00111    | c         |
| Distance (pc)        | 33.691      | a         |

Note—$^a$Gaia Collaboration et al. (2018), $^b$Subasavage et al. (2017), $^c$from http://www.montrealwhitedwarfdatabase.org/evolution.html

excess (Barber et al. 2016), we exclude grains from our models. From the code, we obtain line optical depths, species column densities, and the temperature profile through the gas cloud. With these models, we place constraints on the potential masses and abundances of the C-S gas.

In Section 2, we present new observations of WD 1124-293 with Keck HIRES and an improved co-added MIKE spectrum. In Section 3, we describe how we know the pollution of WD 1124-293 visible in the new, higher resolution HIRES spectrum is not due to the ISM. In section 4, we describe how we model a polluted white dwarf with Cloudy and apply this method to WD 1124-293, showing how we can determine the characteristics of its C-S gas using Cloudy. In short, we build a grid of models and place constraints on the column densities needed for detecting features. In section 5, we present our results and conclude in section 6.

2. OBSERVATIONS

WD 1124-293 was observed 16 times between 1998 and 2011 (Debes et al. 2012) with the MIKE echelle spectrograph (Bernstein et al. 2003). We observed WD 1124-293 using the HIRES echelle spectrograph (Vogt et al. 1994) on the Keck I telescope for 1200s on April 24, 2018. For the HIRES observations, the blue collimator and C5 decker were used with a slit width of 1.148 arcsec, typically giving a spectral resolution of $\sim 40,000$. However, the seeing during the observation was $\sim 0.5$ arcsec, and the effective resolution is $\sim 80,000$. The data were reduced with the MAKEE package. The Ca K line was extracted over two orders and averaged, while the H line was extracted over one order. We continuum-normalized 10 Å regions of the spectrum by fitting a polynomial to the continuum to remove effects due to the instrument response function. The signal-to-noise (S/N) ratio is $\sim 38$ in a 10 Å region (3935 Å to 3945 Å), which corresponds to $\sim 75$ per resolution element. We detect C-S and photospheric absorption at the Ca K line and only photospheric absorption at the Ca H line. We report that no new absorption or emission features have been detected.

Additionally, we reanalyzed the many epochs of spectra presented in Debes et al. (2012). The multiple MIKE epoch spectroscopy was extracted over two orders that contained the Ca H and K lines. For this work, we took the reduced spectra of WD 1124-293 from both the red and blue CCDs at each epoch and flux calibrated the orders against a model DA atmosphere (Koester 2010) with the appropriate $T_{eff}$ and log $g$ (see Table 1) based on WD 1124-293’s parallax and spectro-photometry from APASS, 2MASS, and ALLWISE catalogs. Once all epochs were flux calibrated, we median combined the spectra to a common wavelength grid with a sampling of 0.05 Å between 3350 Å and 5030 Å and 0.08 Å between 5030 Å and 9400 Å. The typical resolution for the MIKE spectra is $\sim 34,000$. Near the Ca K line, the final S/N ratio of the data as measured in the continuum corresponds to $\sim 194$ per resolution element.

We present the Ca absorption line properties for WD 1124-293 in Table 2 for the co-added MIKE spectrum and Keck HIRES spectrum presented in this work. We fit the circumstellar and photospheric absorption features with Gaussians to calculate the equivalent widths of the lines, as well as the FWHMs. The photospheric lines are gravitationally red-shifted. All line center ve-

Table 3. Keck/HIRES Observations of WD 1124-293 and Standards

| Target   | Dist (pc) | Sep (") | Exp (s) |
|----------|-----------|---------|---------|
| WD 1124-293 | 33.7      | –       | 1200s   |
| HIP56280A | 26.3      | 79      | 30s     |
| HIP56280B | 26.3      | 79      | 30s     |
| HIP55864  | 117       | 16      | 100s    |
| HIP55901  | 401       | 24.6    | 100s    |

Note—The distance, separation from WD 1124-293, and exposure time for the target and standards. The observation date was April 24, 2018, at a resolution $\sim 40,000$ with a wavelength range of 3100 - 5950 Å.

1 http://svo2.cab.inta-csic.es/theory/newov2/index.php
Figure 1. Detection of metal photospheric absorption lines for WD 1124-293 using a co-added MIKE spectrum. For each square panel, the MIKE data are shown in black, new Keck HIRES data are shown in teal, and a model of the photosphere is shown in red. The model is convolved with a Gaussian kernel with a width determined by a resolution, \( R = 60,000 \) using a routine from PyAstronomy (https://github.com/sczesla/PyAstronomy, Czesla et al. 2019). The gray region highlights a ±3σ region for the MIKE spectra.

Table 2. Ca absorption line properties for WD 1124-293

| Dataset | \( \lambda_c \) (Å) | \( v_c \) (km/s) | Eq Width (mA) | FWHM (km/s) | \( \lambda_c \) (Å) | \( v_c \) (km/s) | Eq Width (mA) | \( \lambda_c \) (Å) | \( v_c \) (km/s) | Eq Width (mA) |
|---------|---------------------|------------------|----------------|-------------|---------------------|------------------|----------------|---------------------|------------------|----------------|
| MIKE    | 3933.632            | -2.9             | 7.1            | 9.91        | 3934.020            | 27.3             | 113 ± 2        | 3968.841            | 28.25            | 52 ± 1        |
| HIRES   | 3933.637            | -1.9             | 7.8            | 5.97        | 3934.053            | 29.8             | 105 ± 1.5      | 3988.879            | 31.1             | 65 ± 3        |

Note—The Ca H and K line wavelengths are given in air. We only detect a C-S feature at the Ca K line. For the C-S line, the central wavelength of the line is \( \lambda_c \), the Doppler shift velocity is \( v_c \), the equivalent width of the line assuming a Gaussian profile is “Eq Width,” and the full width at half max is FWHM.

3. POLLUTION AND THE ISM

Debes et al. (2012) first investigated the possibility that the weak Ca absorption detected towards WD 1124-293 could be explained by coincident local ISM absorption by comparing against high SNR spectra of stars located closely in the sky. For that study, Debes et al. (2012) looked at HIP 56280A, HIP 55864, HIP 55731, HIP 55901, and HIP 55968, but did not have sufficient parallax information on all of the stars to correctly sort them in terms of increasing distance from the Earth.

Velocities for the Ca K and H lines are also presented in Table 2. The HIRES dataset has the highest resolution of the three sets, and so we use it to constrain the location of the gas. The co-added MIKE spectrum has the highest S/N, so we use it to constrain the abundances of different species. In Figure 1, we show selected photospheric absorption features due to Mg, Ca, and Fe that appear in both the co-added MIKE spectrum and new HIRES spectrum.
Figure 2. The normalized flux for the (a) target and nearby sources (b) - (d) HIP 56280A, HIP 56280B, and HIP 55864. For all panels, the blue line is drawn at a value of 1.0 to guide the eye, the 2019 HIRES data are shown in black, and the red vertical line gives the approximate velocity of the C-S line for WD 1124-293, -2.5 km s\(^{-1}\). In panels (b) - (d), the dashed gray is drawn at 3\(\sigma\) below the continuum. In panel (a), the green curve is the normalized flux from the Magellan MIKE observations described in Debes et al. (2012).

With the advent of the Gaia mission, secure parallaxes now exist for that sample of stars. We re-observed HIP 56280A, HIP 55901, and HIP 55864 and in addition observed HIP 56280B, the physically bound companion to HIP 56280A. HIRES has higher spectral resolution compared to MIKE, and thus higher sensitivity to weak spectral features. The addition of HIP 56280B also ensures tighter constraints on the amount of Ca present in the ISM interior to \(\sim 30\) pc with two independent measurements of that part of the sky.

In order to search for weak lines from the ISM we first had to fit and remove the continuum near the expected rest frame velocity of the Ca K line in question for each standard star. This was relatively straightforward for HIP 55901 and HIP 55864, which show broad Ca absorption due to the rapid rotation of the host stars—the continuum can be fit with a high order polynomial (Debes et al. 2012).

Our approach for HIP 56820A and HIP56820B was slightly different, due to the later spectral type of these two stars. Both objects are roughly consistent with F stars and are likely nearly the same effective temperature and gravity. Both stars show Ca emission in the line core due to stellar activity, though HIP56820A shows stronger emission. For both stars we fit the broad Ca component with a spline fit and then fit the Ca line core with a two component Gaussian curve. We verified that our fits did not unintentionally fit any absorption lines coincident with the rest velocity of the C-S line seen in WD 1124-293. Our resulting continuum fit lines are shown in Figure 2, along with the expected 3\(\sigma\) upper limit to detectable absorption for each star. We estimated this upper limit by taking the standard deviation of flux in the normalized spectra, assuming that we would detect anything 3\(\sigma\) below the continuum level. We note that we do not show the spectrum of HIP 55901, which shows strong absorption consistent with that observed previously in Debes et al. (2012). None of these comparison stars near WD 1124-193 show Ca absorption at the velocity of the observed Ca line, so we confidently rule out an ISM contribution to the WD spectrum.

4. MODELING WD CIRCUMSTELLAR GAS WITH CLOUDY

4.1. Cloudy Model Inputs

We aim to constrain the abundances of metals in the circumstellar gas of WD 1124-293. A Cloudy input file requires an ionizing source, the geometry of the gas, the density of hydrogen in the gas, and the abundances of He to Zn, relative to H. In this section, we describe how we determine these inputs for WD 1124-293 and how we use the Cloudy output, thereby describing our method for using Cloudy to model the C-S environment of a polluted white dwarf. Calculations were performed with version 17.01 of Cloudy, last described by Ferland et al. (2017).

4.1.1. The ionizing source

For the Cloudy model, we use an interpolated Koester DA photosphere (Koester 2010; Tremblay, & Bergeron 2009)\(^2\) with a temperature of 9420 K and luminosity of 0.00111L\(_\odot\) as the input, or ionizing continuum. The continuum is mapped to an energy mesh with a resolution of 0.05, (20x the native course grid of \(R \sim 300\)).

4.1.2. Geometry

The geometry of the C-S gas around WD 1124-293 is unknown. We choose to set the geometry in a disk, rather than a sphere because we have shown that it is highly unlikely that the ISM is the source of the pollution. Debes et al. (2012) place constraints on the location of the C-S gas, with a minimum distance of

\(^2\) Models were downloaded from the Spanish Virtual Observatory database.
$7^{+11}_{-3} R_{\text{wd}}$, maximum distance of 32000 AU, and dynamical estimate of $\sim 54 R_{\text{wd}}$, where $R_{\text{wd}}$ is the radius of WD 1124-293. The dynamical estimate of the location of the gas is determined assuming the gas is in a circular Keplerian orbit and using the FWHM of the gas absorption feature to determine the upper limit to the disk’s orbital velocity. The “dynamical” distance of the gas from the WD, $R_{\text{Kep}}$, is

$$R_{\text{Kep}} \approx (GM_{\text{wd}})^{1/3} \left[ \frac{2R_{\text{wd}}}{\text{FWHM} \text{ (cm/s)}} \right]^{2/3},$$

where $G$ is the gravitational constant. From the new HIRES dataset, we measure the FWHM of the C-S absorption feature assuming the line profile is Gaussian. With the resulting FWHM $\sim 6$ km/s, and the radius listed in Table 1, $R_{\text{Kep}} \sim 106 R_{\text{wd}}$ for WD 1124-293, a value almost double that in Debies et al. (2012) due to the high spectral resolution of the HIRES data. $R_{\text{Kep}}$ is the best estimate of the minimum distance of the gas to the star and it depends on the width of the absorption feature. If the C-S absorption feature were more narrow, then $R_{\text{Kep}}$ would be larger.

The outer edge of the gas is unknown, but we can consider a sublimation radius and a tidal disruption radius. The sublimation radius, $R_{\text{sub}}$, is the distance at which the equilibrium temperature of particles equals their sublimation temperature, $T_{\text{sub}}$, with

$$R_{\text{sub}} = \frac{R_{\text{wd}}}{2} \left( \frac{T_{\text{wd}}}{T_{\text{sub}}} \right)^2. \tag{2}$$

This equation represents the smallest possible sublimation radius for optically thin distributions of dust and it assumes the particles absorb and emit radiation perfectly. $R_{\text{sub}}$ depends on the shape, size, and composition of the particle. Graphite grains (0.01μm) and astronomical silicate grains (0.1 μm) would sublimate at 54 $R_{\text{wd}}$ and 93 $R_{\text{wd}}$, respectively (see Figure 3). In Section 5, we discuss why the detectable gas at $R_{\text{sub}}$ is farther than $R_{\text{sub}}$.

The tidal disruption radius, $R_{\text{tide}}$ (Davidsson 1999; Jura 2003; Veras et al. 2014), also depends on the composition of the material with

$$\frac{R_{\text{tide}}}{R_{\odot}} = C_{\text{tide}} \left( \frac{M_{\text{wd}}}{0.6 M_{\odot}} \right)^{1/3} \left( \frac{\rho_b}{3 \text{ g cm}^{-3}} \right)^{-1/3}, \tag{3}$$

where $C_{\text{tide}}$ has typical values of 0.85 to 1.89 (Bear & Soker 2013), and $\rho_b$, the density of the disrupting body satisfies $\rho_b \geq 1 \text{ g cm}^{-3}$ (Carr 2012; Veras et al. 2014). For WD 1124-293, the maximum tidal disruption radius is $R_{\text{tide}} \sim 200 R_{\text{wd}}$. We show typical ranges of tidal disruption radii for comets and asteroids ($R_{\text{tide,comet}}$ and $R_{\text{tide,asteroid}}$) in Figure 3.\(^3\)

We take $R_{\text{Kep}}$ as our minimum radius of the gas and assume that these radii follow the relation $R_{\text{tide}} > R_{\text{Kep}} > R_{\text{sub}}$ (see Figure 3). We set the gas to extend from 100 $R_{\text{wd}}$ to 200 $R_{\text{wd}}$ (approximately $R_{\text{Kep}}$ to $R_{\text{tide}}$). The aspect ratio of the gas disk is $h/r \sim 10^{-3}$ (Metzger et al. 2012), so we truncate the gas to a cylinder with a height of 10% $R_{\text{wd}}$. We discuss the implications of this relation among radii in Section 5.

4.1.3. Hydrogen density

Most planetesimals accreted onto WDs are water poor, so there should be very little hydrogen gas present around WD 1124-293, assuming a planetesimal origin (see section 5.3 of Jura & Young 2014, and references therein). However, Cloudy uses the number density of hydrogen, $n_H$, to set the conditions of a cloud. If a C-S gas spectrum has features due to hydrogen, one could probe the maximum amount of hydrogen present in the system by calculating the column density due to H, $N_H$, assuming every H atom participates in the line transition. With no such features and a gas temperature too low for the Balmer $\text{H}_\alpha$ line to form, we turn to a geometrical argument.

The area of the column along the line of sight which subtends the white dwarf is $\sim 2 \times H \times R_{\text{wd}}$ and the

\(^3\) For comparison, for comet Shoemaker Levy 9 had $C_{\text{tide}} \sim 1.31$ and $\rho_b \lesssim 0.702$ (Boss 1994), and would have a disruption radius of $\sim 110 R_{\text{wd}}$ near WD 1124-293.
volume is \(2 \times H \times \Delta R \times R_{\text{wd}}^2\), where \(H\) is the gas height and \(\Delta R = R_{\text{out}} - R_{\text{in}}\) is the gas extent in units of \(R_{\text{wd}}\), with an outer radius, \(R_{\text{out}}\), and an inner radius, \(R_{\text{in}}\). The column density is equal to the number density times the volume of the gas column, divided by the area of the column along the line of sight which subtends the white dwarf. Solving for \(n_H\),

\[
n_H \leq \frac{N_H}{\Delta R \cdot R_{\text{wd}}}. \tag{4}
\]

We do not know the H number density, so we choose to explore a range such that \(-1 \leq \log(n_H/\text{cm}^{-3}) \leq 10\). The minimum value is typical of the diffuse H II \((n_H \sim 0.3 - 10^4 \text{ cm}^{-3})\) and warm neutral medium \((n_H \sim 0.6 \text{ cm}^{-3})\) phases of the ISM (Draine 2011). For a maximum plausible value, we rely on observations of specific circumstellar disks around protoplanetary and transition disks.\(^4\) For gas with a height of 10% \(R_{\text{wd}}\), extending from 100 \(R_{\text{wd}}\) to 200 \(R_{\text{wd}}\), with \(\log N_H \sim 19\), \(n_H \lesssim 10^6 \text{ cm}^{-3}\). We therefore explore the dependence of our models on the hydrogen density with a grid of models that have \(-1 \leq \log(n_H/\text{cm}^{-3}) \leq 10\). For each model, the hydrogen density is constant with distance from the star. The most likely model is the one that minimizes the amount of H while allowing for metal lines to form.

### 4.1.4. C-S Gas Abundances

Calcium is the only C-S gas with a positive detection in WD 1124-293. Therefore, we consider the abundances of elements relative to Ca. Table 4 lists the elements that are typical polluters of WDs for which we have photospheric abundance limits, and are thus explored with our modeling. We focus on the strongest optical transitions for these species that have photospheric detection (Mg I 3838 and Fe II 3228), and detection upper limits (K I 4043, Ni I 3480, Mn I 4032, Al I 3961, Si I 3905, Na I 5890). All other elements from He to Zn are left at the default solar composition values, relative to Ca. We approach the abundances in this way for two reasons. First, the ratios of potential metals of interest are very similar for a solar and chondritic composition (see Figure 6). Second, there is thus far only one detected C-S feature in the optical part of the spectrum for WD 1124-293. A UV spectrum would likely show more absorption features that could be used to better constrain the C-S metal abundances (see Figure 9).

We use the C-S column density of Ca II 3934 to constrain the modeling by varying the abundance ratios of metals relative to calcium. Beginning with a hydrogen number density \(n_H = 0.1 \text{ cm}^{-3}\) (a lower limit inspired by low density ISM regions), we first find abundance ratios that, when paired with the overall hydrogen density, result in optical depths that lead to a calculated absorption line with a depth at the 3σ limit to the observed continuum. For the rest of the metals considered, we ensured that their abundances were such that no lines were formed (see Figure 5). We then fix those abundance ratios and vary the hydrogen density over 10 orders of magnitude, while increasing the abundance of Ca relative to H to explore the model dependence on the amount of hydrogen present. The resulting grid of models is presented in Figure 4.

#### 4.2. Cloudy Model Output

We choose to save the general overview, line optical depths, and line population for each Cloudy run. The general overview contains an output transmitted spectrum, but it does not include line broadening mechanisms, such as micro thermal motion, macro circular motion, or instrument effects, for an unresolved line. The net transmitted spectrum from Cloudy can however be used to check the validity of a set of input parameters (by investigating whether other absorption or emission features are produced), and to predict a spectrum ranging from the far UV to near IR (see Discussion).

We use the optical depth and column density to compare Cloudy models to MIKE spectrum. We save the optical depths, \(\tau\), for all species with \(\tau > 0.001\) to calculate an absorption line profile, and the populations of upper and lower levels for all lines to calculate the column densities of different species. The column densities are calculated for each line by multiplying the lower level population per zone by the length of the zone. Zones are automatically calculated by Cloudy. We only consider the lower level populations in the column density calculation because we are not in a regime where stimulated emission is important.

#### 5. RESULTS AND DISCUSSION

We investigate the gas toward WD 1124-293 to explore the conditions necessary to produce the observed absorption. We further constrain the location and amount of Ca present in the C-S gas, reproduce the observed C-S Ca K absorption line profile and place upper limits to the amounts of H, Mg, Ca, Fe, and other metals present around WD 1124-293 by using Cloudy to determine their optical depths and expected line column densities. We place limits on the total amount of gas and show the temperature profile through the model disk. We then connect these results to other similar studies and argue for future UV observations.

\(^4\) The maximum possible value of \(N_H\) for TW Hydrae is \(\log(N_H/\text{cm}^{-2}) \sim 19.75\) (Herczeg et al. 2004), and the H column density for \(\beta\) Pictoris is \(\log(N_H/\text{cm}^{-2}) \sim 18.6 \pm 0.1\), (Wilson et al. 2017).
emitting at a range of radii (0.6–1.2R\(_\text{wd}\) or 50–100R\(_\text{wd}\)), with a concentration at \( \sim 100R\text{wd} \) (Manser et al. 2016).

5.2. Column Densities

We determine the column density of the C-S Ca gas by finding the range of optical depths that lead to an absorption feature at a depth of \( \pm 3\sigma \) relative to the depth of the Ca C-S line in the MIKE dataset, resulting in \( \log N(Ca) = 11.01^{+0.26}_{-0.09} \) (Debes et al. 2012 find \( \log N(Ca) = 11^{+0.3}_{-0.2} \)). The downward trend in column density with increasing hydrogen number density seen in Figure 4 is due to a decrease in the calculated electron density. To investigate the dependence of our modeling on hydrogen, we explored 10 orders of magnitude in hydrogen number density, fixing the relative abundance ratios for all elements. The hydrogen number density is degenerate with the hydrogen abundance, so we are only able to constrain the amount of hydrogen with a geometrical argument described in Section 4.2.2. The upper limits to the abundances of these different species are presented in Table 4.

5.3. Line Profiles

The Ca C-S absorption line is only marginally resolved, so we construct the absorption line profile by taking the convolution of (1) a Voigt line profile broadened due to Maxwellian distributed velocities and a gas temperature determined by Cloudy and (2) a Gaussian kernel with a width determined by the resolution of the HIRES spectrum.\(^5\) The Voigt line profile is approximated using a series expansion as \( \phi(x) \propto \exp(-x^2) + a/(\pi^{1/2}x^2) + 2a/(\pi^{3/4}x^4) \), where \( a \) is the dampening constant for the transition in question, \( x = (\nu - \nu_0)/\Delta\nu_{\text{Dopp}}, \nu_0 \) is the center frequency for line, and \( \Delta\nu_{\text{Dopp}} \) is the FWHM of the line. The output intensity is \( I = I_0 \exp(-\tau\phi(x)) \), where \( \tau \) is the optical depth at line center. The output intensity considering the velocity profile is \( \propto \exp(-\tau(\phi(x) + \phi(v))) \).

We show the calculated line profiles for the strongest optical transitions of these metals in Figure 5.

5.4. Metals in the gas around WD 1124-293

The calculated calcium K line column density corresponds to an abundance of 1.35 relative to hydrogen when \( n_H = 0.1 \text{ cm}^{-3} \). As we increased the hydrogen number density, we let the calcium and hydrogen abundances vary from \( -8.90 < \log n(Ca)/n(H) < 1.35 \) and \( -1 < \log n(H) < 11 \). For the lowest H number density,

\(^5\) If the absorption line were resolved, we would also convolve the Voigt line profile with a velocity profile, \( \phi(v) \) describing the bulk motion of the gas disk.
Figure 5. Calculated line profiles for species of interest. The calculated or model line profiles are shown in red. The black curves show the co-added MIKE spectra. The blue region highlights a ±3σ region for the MIKE spectra. The strengths of the model absorption lines are limited by column density upper limits estimated from the MIKE spectrum. For the Ca features, the deeper photospheric component is gravitationally red-shifted.

the abundances of Mg and Fe that produce an absorption feature at a depth of 3σ are log \( n(Mg)/n(H) = 7.85 \) and log \( n(Fe)/n(H) = 5.70 \). We then fix the ratios of Mg and Fe relative to Ca with increasing density, such that log \( n(Mg)/n(Ca) = 6.5 \) and log \( n(Fe)/n(Ca) = 4.4 \) for all models shown in Figure 4. All other element abundances, \( El \), are set such that log \( n(El)/n(Ca) \) is constant for models with increasing \( n_H \). Figure 4 shows how the column density for the strongest observable optical transition in a species varies with increasing H number density and fixed element abundance ratios.

5.5. The mass of the gas around WD1124-293

Given our geometrical constraints (inner radius, \( R_{in} \) and outer radius, \( R_{out} \)) and assumed disk height, \( H \), the volume of the gas disk is \( V = \pi H (R_{out}^2 - R_{in}^2) \), and
Table 4. Photospheric and Circumstellar Metal Abundances and Masses

| El   | Phot | log \(M_{\text{EI}}\) (g yr\(^{-1}\)) | C-S | log \(M_{\text{C-S}}\) (g) |
|------|------|-------------------------------|-----|----------------------|
| H    | 1    | -                             | 1   | < 8.95               |
| Na   | < -8.30 | < 13.62 | < 3.35 | < 10.67 |
| Mg   | -7.689 ± 0.024 | 14.30 | 7.85 | < 15.19 |
| Al   | < -8.80 | < 13.24 | < 7.05 | < 14.44 |
| Si   | < -7.50 | < 14.54 | 6.65 | < 14.06 |
| K    | < -8.60 | < 14.20 | < 7.05 | < 14.61 |
| Ca   | -8.872 ± 0.188 | 13.33 | 1.357 ± 0.086 | 8.92 ± 0.1 |
| Ti   | < -8.50 | < 13.86 | < 1.2 | < 8.84 |
| Mn   | < -8.50 | < 14.01 | < 4.65 | < 12.34 |
| Fe   | -7.814 ± 0.130 | 14.69 | < 5.7 | < 13.40 |
| Ni   | -8.40 | < 14.10 | < 5.35 | < 13.08 |
| Total | < 15.38 |

Note: Photospheric and circumstellar (C-S) abundances by number relative to hydrogen, log\(n(\text{El})/n(\text{H})\), for our model. We show the C-S abundances that correspond to a model with \(n_{\text{H}} = 0.1\) cm\(^{-3}\).

Figure 6. Abundances relative to calcium for metals typically present in photospheric pollution of WDs. We show the upper limits for our Cloudy model with \(n_{\text{H}} = 0.1\) cm\(^{-3}\) with the star markers and the abundances derived from the photospheric model considering diffusion with the black hexagons. We only had a marginal detection of silicon in the photosphere and provide an upper limit there. \(^a\)Allégre et al. (2001), \(^b\)Holweger (2001); Grevesse & Sauval (1998), \(^c\)Cowie & Songaila (1986), and \(^d\)Lodders (2003).

Figure 7. Top panel: The temperature profile through the disk. Some useful output from Cloudy is the ability to know the temperature profile within the cloud. Modeling of regions usually assume an isothermal environment which is not the case for many of the models. Lower panel: Optical depth with distance for the Ca K line, as well as the Fe and Mg lines responsible for heating and cooling, respectively.

The total gas mass \(M_{\text{tot}}\) is given by

\[
M_{\text{tot}} = V \cdot \left( \sum (10^{n_{\text{H}}} \cdot 10^{abn} \cdot m_{\text{EI}}) + 10^{n_{\text{H}}} \right) \cdot m_{\text{H}},
\]

where \(n_{\text{H}}\) is the hydrogen number density, \(abn\) is the abundance relative to hydrogen, \(m_{\text{EI}}\) is the mass of an element in atomic mass units, and \(m_{\text{H}}\) is the mass of the hydrogen atom in g. Using the abundances and hydrogen density from our model with a maximum amount of hydrogen \((n_{\text{H}} = 10^{3} \text{ cm}^{-3})\), we place an upper limit on the total gas mass, log\(M_{\text{tot}}\) \(\approx 16.12\) g or \(\sim 30\) times the mass of C-type asteroid 162173 Ryugu (4.50 \(\times\) 10\(^{14}\) g, Watanabe et al. 2019). Using our model with a minimum amount of hydrogen \((n_{\text{H}} = 10^{-1} \text{ cm}^{-3})\), the upper limit on the total gas mass is log\(M_{\text{tot}}\) \(\approx 15.38\) g or \(\sim 5\) times the mass of Ryugu. The lower limit is set by the total amount of mass required to produce the Ca feature, so the C-S gas mass, log\(M_{\text{C-S}}\) is constrained to 8.92 < log\(M_{\text{C-S}}\) < 16.12. Figure 6 shows the relative abundances of Mg, Si, Ca, and Fe for our best fit and the relative abundances of those same metals in the photosphere.

5.6. Gas Temperature

Cloudy also provides the temperature throughout the gas. For this model, the gas temperature ranges from \(\sim 4994\) K to \(\sim 3965\) K. We show the temperature profile for the best fit model in Figure 7, also including the
The strongest expected lines in the optical come from the enhanced Mg, Ca, and Fe in our solar-like composition around WD1123-293 (see Figure 8). To obtain the optical depths of the two strongest lines at the same depths in the disk.

In our Cloudy models, the heating is dominated by Fe II and the cooling is dominated by Mg II (see bottom panel of Figure 7). The temperature of the gas is determined by Cloudy self-consistently and depends on heating and cooling mechanisms. Other efforts to model C-S around WDs tend to assume the temperature is isothermal, though at least one group calculates the temperature at different locations in the disk assuming a Shakura and Sunyaev viscous $\alpha$-disk using the accretion-disk code AcDc (Hartmann et al. 2016; Nagel et al. 2004). For a WD with $T_{\text{eff}} = 20900$ K, Hartmann et al. (2016) find the gas temperature decreases to a minimum value $\sim 6000$ K a third of the way through the disk before rising to a maximum of $\sim 6600$ K at the outer edge. The temperature profile of this gas disk is very different from that of WD 1124-293, as shown in the top panel of Figure 7. For WD 1124-293, the gas temperature profile declines roughly as the $T \propto r^{-0.35}$, with a mild inversion at the inner edge of the disk. Further investigation is needed to understand this discrepancy. Additionally, for hotter WDs, the temperature range probed by Cloudy could be much larger than the 20% changes seen for WD 1124-293.

5.7. Strongest transitions and a need for UV observations

The strongest expected lines in the optical come from the enhanced Mg, Ca, and Fe in our solar-like composition around WD1123-293 (see Figure 8). To obtain the abundances of heavy elements for the photosphere, we proceed in a similar way as described in Xu et al. (2019), by computing grids of synthetic spectra for each element of interest using a pure DA atmospheric structure assuming the stellar parameters previously determined by fitting the photometric data and parallax measurement. The abundances are then obtained by minimizing $\chi^2$ between the normalized spectroscopic data and the grid spectrum. Trace amounts of metals have a negligible effect on the thermodynamic structure for the grid spectrum.

The strongest transitions for most of these species that would help constrain the gas composition and therefore, the sublimation temperature (O, Fe, Si, and Mg), are in the UV. Our polluted photospheric model for WD 1124-293 predicts very strong Mg and Fe absorption lines at UV wavelengths, and as such, our upper limits are likely too large (see Figure 9).

FUV observations of other dusty WDs with $T_{\text{eff}} \geq 12000$ K have shown absorption lines from as many as 19 unique elements (GD 362, Xu et al. 2013), providing detailed information about planetary material that orbits another star. For example, we can look for correlations between progenitor mass and elemental abundance, or seek to find correlations with specific elemental enhancements, such as Ca. With UV observations, better constraints would be placed on Mg and Fe, helping to further constrain the relative abundances of these metals.

5.8. Other work modeling WDs with Cloudy

Gänsicke et al. (2019) use Cloudy to model the C-S gas of WDJ0914+1914 viewed in emission, which contains signatures of the disruption and subsequent accretion of a giant planet. WDJ0914+1914 has $T_{\text{eff}} = 27743 \pm 310$K and its photosphere shows evidence of ongoing accretion of oxygen and sulfur. At this temperature, the C-S gas is photoionized, and contains enough hydrogen for oxygen, sulfur, and H$\alpha$ emission lines to form. The emission features are doubly peaked, indicating the gas is in disk undergoing Keplerian rotation. In their work, the C-S abundances for O and S are consistently determined by two independent methods for the first time.

With this work, we follow up with the second instance to date of determining gas composition with two independent measurements, and show for the first time how to place constraints on abundances when only absorption features are present. This proof of concept for modeling absorption with Cloudy will be useful when applied to more complicated systems, such as WD 1145+017.
5.9. *Our proof of concept in the context of WD 1145+017*

WD 1145+017 was first shown to have a transiting, disintegrating planetesimal by Vanderburg et al. (2015) and has been since been the subject of much observation (e.g. Xu et al. 2016; Cauley et al. 2018; Croll et al. 2017; Xu et al. 2019; Fortin-Archambault et al. 2020) due to days to week transit and spectroscopic variability. Fortin-Archambault et al. (2020) present a new characterization of WD 1145+017’s absorption features, showing how a simple model of nested concentric rings with high eccentricity can help account for the majority of the observed features, which include asymmetrical line profiles and Doppler shifting of the absorption features. These features are also seen in a number of other polluted WDs showing emission lines (e.g., Wilson et al. 2014; Manser et al. 2019; Gänsicke et al. 2019).

The addition of high-resolution spectra to the analysis in Fortin-Archambault et al. (2020) helped disentangle closely spaced features that led to an overestimated prior abundance calculation in Xu et al. (2016). A code like Cloudy could be useful in identifying components of such blends to obtain accurate abundances. They also observe Si IV features in the UV at 1393.76 Å and 1402.77 Å and invoke an additional low eccentricity component to explain the presence of such highly ionized species. Cloudy would naturally be able to probe the conditions needed to produce Si IV features with its self-consistent microphysics.

6. CONCLUSION

With this work, we outline how to use the Cloudy radiative transfer code to model C-S gas viewed in absorption around WD 1124-293. We create a Cloudy grid of models for C-S gas around WD 1124-293 to explore the abundances of elements from He to Zn relative to hydrogen, and obtain line optical depths, species column densities, and the temperature profile through the gas disk. Our best fit model minimizes the total amount of hydrogen, while still producing the observed Ca K C-S absorption feature.

We detect photospheric absorption features due to Mg and Fe for the first time, determine a new location for the C-S gas, and place upper limits on abundances of other metals in the photosphere. The upper limit C-S abundance ratios of Mg, Si, and Fe to Ca are also consistent with the photospheric abundance ratios, and with a chondritic/bulk Earth composition.

With these models, we place constraints on the potential masses and abundances that could result in a spectrum dominated by calcium species for WD 1124-293, find that the C-S is likely not isothermal, and show that the Cloudy microphysics code, which is typically used to model active galactic nuclei and HII regions, can also be used to model C-S gas absorption features of polluted white dwarfs. UV spectroscopic observations of WD 1124-293 are needed to further constrain the composition of its C-S gas.

Looking forward, we intend to explore the properties of C-S gas around DA WDs with temperatures 6000 K to 27,000 K using Cloudy, and will make the grid of gas properties publicly available (Steele et al. *in prep*).

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\textbf{Facilities:} Magellan(MIKE), Keck(HIRES)

\textbf{Software:} astropy (Astropy Collaboration et al. 2013), Cloudy (Ferland et al. 2017), PyAstronomy (Czesla et al. 2019)

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