ROCKY EXTRASOLAR PLANETARY COMPOSITIONS DERIVED FROM EXTERNALLY POLLUTED WHITE DWARFS

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ABSTRACT

We report Keck High Resolution Echelle Spectrometer data and model atmosphere analysis of two helium-dominated white dwarfs, PG1225−079 and HS2253+8023, whose heavy pollutions most likely derive from the accretion of terrestrial-type planet(esimals). For each system, the minimum accreted mass is \( \sim 10^{22} \) g, that of a large asteroid. In PG1225−079, Mg, Cr, Mn, Fe, and Ni have abundance ratios similar to bulk Earth values, while we measure four refractory elements, Ca, Sc, Ti, and V, all at a factor of \( \sim 2\)–3 higher abundance than in the bulk Earth. For HS2253+8023 the swallowed material was compositionally similar to bulk Earth in being more than 85% by mass in the major element species, O, Mg, Si, and Fe, and with abundances in the distinctive proportions of mineral oxides—compelling evidence for an origin in a rocky parent body. Including previous studies we now know of four heavily polluted white dwarfs where the measured oxygen and hydrogen are consistent with the view that the parents’ bodies formed with little ice, interior to any snow line in their nebular environments. The growing handful of polluted white dwarf systems with comprehensive abundance measurements form a baseline for characterizing rocky exoplanet compositions that can be compared with bulk Earth.

Key words: planets and satellites: composition – stars: abundances – stars: individual (HS2253+8023, PG1225−079, G241-6) – white dwarfs

Online-only material: color figures

1. INTRODUCTION

Accretion by white dwarfs (WDs) of tidally disrupted bodies from their planetary systems (Jura 2003) has become the most viable explanation for the presence of high-Z (atomic number \( Z > 2 \)) elements in the vast majority of polluted DAZ, DBZ, and DZ white dwarf atmospheres with \( T_{\text{eff}} < 20,000 \) K (Gänsicke et al. 2006; Jura 2008; Zuckerman et al. 2010; Farihi et al. 2010a, and references therein). The basic idea is that smaller planetary bodies such as asteroids or dwarf planets can acquire highly eccentric orbits by perturbations from larger planetary bodies, especially considering the dynamical rearrangement of the planetary system during stellar evolution and mass loss (Debes & Sigurdsson 2002). Bonsor et al. (2011) demonstrate that the post-stellar mass loss evolution of a planetesimal belt can supply the required mass influx to explain observed polluted WD accretion rates. Objects that journey within the Roche radius of the WD will experience tidal shredding, forming a disk of dust and/or gas (Jura 2003, 2008), and subsequently accrete into the star’s, otherwise pure, hydrogen and/or helium atmosphere. This natural mechanism offers the potential to measure the distilled elemental constituents of a planetary parent body or bodies—a unique and powerful tool, indeed.

High-resolution and high-sensitivity spectroscopy, along with state-of-the-art model atmospheres (Koester et al. 2009, 2010; Tremblay & Bergeron 2009; Dufour et al. 2010; Vennes et al. 2010, 2011), has opened the door to detailed studies of WD atmospheres and the high-Z material that pollutes them. To date, a handful of WDs with very rich spectra have been studied at high resolution and high sensitivity, beginning with the Keck/High Resolution Spectrometer (HIRES) follow-up (Zuckerman et al. 2007) of GD362, whose extreme high-Z-rich atmosphere was pointed out by Gianninas et al. (2004) and Kawka & Vennes (2006). The detection of oxygen (O) along with the other major elements (Mg, Si, and Fe) in GD40’s polluting parent body (Klein et al. 2010) established chemical evidence—the stoichiometric balance of mineral oxides—for rocky extrasolar planetesimals. Ongoing discoveries of polluted WDs displaying all major terrestrial elements (Vennes et al. 2010; Dufour et al. 2010; Zuckerman et al. 2010; Farihi et al. 2011) signify that externally polluted WDs have become practical measuring devices of the elemental compositions of rocky exoplanets. Bond et al. (2010) predict a wide diversity of terrestrial exoplanets including Earth-like, refractory-rich, and carbon-rich objects. Polluted WDs provide real data at the level of detail needed to make discerning measurements (e.g., Zuckerman et al. 2011).

In this paper we report the detailed analysis of HIRES spectra of HS2253+8023 (hereafter HS2253, \( V_{\text{mag}} = 16.1 \), DBAZ, \( T_{\text{eff}} \sim 14,400 \) K) and PG1225−079 (hereafter PG1225, \( \equiv K 789–37, V_{\text{mag}} = 14.8, \) DZAB, \( T_{\text{eff}} \sim 10,800 \) K). Both stars were previously known to display features of H, Mg, Si, Ca, and Fe mainly from low (\( \sim 6 \) Å) resolution IUE and optical data (Koester et al. 1990; Friedrich et al. 1999; Wolff et al. 2002). Calcium in PG1225 was also (re)observed and analyzed from the ESO SN Ia progenitor (SPY) survey (Koester et al. 2005b). The HIRES observations provide a new and important detection of oxygen (O) along with the other major elements (Mg, Si, and Fe) in GD40’s polluting parent body (Klein et al. 2010) established chemical evidence—the stoichiometric balance of mineral oxides—for rocky extrasolar planetesimals. Ongoing discoveries of polluted WDs displaying all major terrestrial elements (Vennes et al. 2010; Dufour et al. 2010; Zuckerman et al. 2010; Farihi et al. 2011) signify that externally polluted WDs have become practical measuring devices of the elemental compositions of rocky exoplanets. Bond et al. (2010) predict a wide diversity of terrestrial exoplanets including Earth-like, refractory-rich, and carbon-rich objects. Polluted WDs provide real data at the level of detail needed to make discerning measurements (e.g., Zuckerman et al. 2011).
in which derived abundances relative to helium are typically uncertain by 0.2–0.7 dex. Infrared studies show that HS2253 does not have an infrared excess (Farihi et al., 2009), and PG1225 has just a subtle infrared excess appearing only at 7.9 μm (Farihi et al., 2010b; Kilic et al., 2008a). Notwithstanding the lack of detected circumstellar dust, we demonstrate that these systems have accreted an appreciable amount of material with terrestrial planetesimal composition.

We also report the detection of Ca II H&K emission cores in PG1225, the first time seen in a WD. Other peculiar line profiles observed with HIRES are narrow absorption cores in helium lines of PG1225, GD362, and GD16, which are displayed in Figure 2. The data were acquired with the HIRES (Vogt et al., 1994) on the Keck I telescope of Mauna Kea Observatory. Table 1 is the observation log. Typically, a 1′′148 slit width was used, providing a spectral resolution of $R = \lambda / \Delta \lambda \approx 40,000$. To compensate for inferior seeing on 2008 November 15, a 1′′722 slit was used, resulting in a resolution of $R \sim 28,000$ for those spectra. Before combining exposures of the same star with differing setups, the higher resolution spectra were degraded by Gaussian convolution to approximate the lower resolution spectra.

**2. OBSERVATIONS AND MEASUREMENTS**

The data were acquired with the HIRES (Vogt et al., 1994) on the Keck I telescope of Mauna Kea Observatory. Table 1 is the observation log. Typically, a 1′′148 slit width was used, providing a spectral resolution of $R = \lambda / \Delta \lambda \approx 40,000$. To compensate for inferior seeing on 2008 November 15, a 1′′722 slit was used, resulting in a resolution of $R \sim 28,000$ for those spectra. Before combining exposures of the same star with differing setups, the higher resolution spectra were degraded by Gaussian convolution to approximate the lower resolution spectra.

**Data reduction and absorption line measurements were carried out using PyRAF in a similar manner as described for GD40 in Klein et al. (2010). For the present work we took some extra steps, since in addition to a fully continuum-normalized version of each spectrum, we also wanted a version that preserved the higher resolution spectra. Before combining exposures of the same star with differing setups, the higher resolution spectra were degraded by Gaussian convolution to approximate the lower resolution spectra.**
The number density of absorption lines increases dramatically toward UV wavelengths. The absolute flux level and the overall continuum slope are uncalibrated, which is not a problem for the line measurements which are always made relative to their local continuum.

For each transition, the shift of line center from the laboratory wavelength is measured, and converted to a heliocentric velocity. We use the average line velocity for a systemic value, and Doppler shift the models to the measured frame of the WD, which are plotted in red on the figures of spectra. The net systemic heliocentric velocities, including the stars' gravitational redshifts, are $4 \pm 4 \text{ km s}^{-1}$ for HS2253 and $49 \pm 3 \text{ km s}^{-1}$ for PG1225. From the histogram of line velocity measurements shown in Figure 14, for PG1225 we found a range of outliers (filled bars in the figure) that represent a detectable shift of the set of Fe I lines (see also Figure 12). These are not of an interstellar origin since, as indicated in Table 2, most transitions arise from excited atomic levels. An analogous shift for Si II lines has been examined and modeled with Stark shifts by Vennes et al. (2011); a similar process may be responsible for the effect on Fe I in PG1225, and further investigation remains for future work. HS2253’s velocity measurements do not indicate any distinctive sub-populations.

With such high-sensitivity observations of PG1225 a new feature has turned up (literally) that we have not seen before in WDs—emission cores in the Ca II H&K lines as shown in Figure 15. The emission features are seen in all three pollutants, and some Fe I lines, and the Si II lines have been examined and modeled with Stark shifts by Vennes et al. (2011); a similar process may be responsible for the effect on Fe I in PG1225, and further investigation remains for future work. HS2253’s velocity measurements do not indicate any distinctive sub-populations.
| Ion | $\lambda^a$ | $\chi$ | log $gf$ | Equivalent Width (mA) |
|-----|-------------|--------|----------|-----------------------|
|     | (Å)         | (eV)   |          |                       |
| H\textsc{i} | 6562.79 | 10.20 | 0.71 | 10,500 (2,000) | 850 (120) | <250 |
| H\textsc{i} | 4861.32 | 10.20 | -0.02 | 3,500 (1,500) | 120 (30) | ... |
| O\textsc{i} | 7771.94 | 9.15 | 0.37 | <250 | 350 (90) | 250 (50) |
| O\textsc{i} | 7774.16 | 9.15 | 0.22 | ... | 190 (50) | 170 (50) |
| O\textsc{i} | 7775.39 | 9.15 | 0.00 | ... | 220 (110) | 90 (40) |
| O\textsc{i} | 8446.35 | 9.52 | 0.24 | ... | 380 (190) | 210 (50) |
| Na\textsc{i} | 5895.95 | 0.12 | <50 | <120 | ... |
| Mg\textsc{i} | 3829.35 | 2.71 | -0.23 | In 3800 interval | 50 (6) | 15 (5) |
| Mg\textsc{i} | 3832.30 | 2.71 | -0.36, 0.12 | In 3800 interval | 220 (40) | 75 (14) |
| Mg\textsc{i} | 3838.29 | 2.72 | 0.39, -0.35 | In 3800 interval | 470 (40) | 106 (14) |
| Mg\textsc{i} | 5172.68 | 2.71 | -0.45 | 30 (15) | 70 (40) | 31 (15) |
| Mg\textsc{i} | 5183.60 | 2.72 | -0.18 | 90 (45) | 170 (40) | 52 (11) |
| Mg\textsc{ii} | 4481 | 8.86 | 0.74, -0.56, 0.59 | 90 (20) | 1040 (110) | 470 (50) |
| Mg\textsc{ii} | 7877.05 | 10.00 | 0.39 | ... | 270 (110) | 110 (25) |
| Mg\textsc{ii} | 7896.04 | 10.00 | -0.31 | ... | In Mg \textsc{ii} 7896.36 | In Mg \textsc{ii} 7896.36 |
| Mg\textsc{ii} | 7896.36 | 10.00 | 0.65 | ... | 460 (130)$^e$ - Mg \textsc{ii} | 250 (40)$^e$ - Mg \textsc{ii} |
| Al\textsc{i} | 3961.52 | 0.04 | -0.32 | <40 | ... |
| Si\textsc{ii} | 3905.52 | 1.91 | -0.74 | <35 | ... |
| Si\textsc{ii} | 3856.02 | 6.86 | -0.41 | ... | 190 (20) | 74 (19) |
| Si\textsc{ii} | 3862.59 | 6.86 | -0.76 | ... | 190 (13) | 38 (8) |
| Si\textsc{ii} | 4128.05 | 9.84 | 0.36 | ... | 67 (25) | 27 (4) |
| Si\textsc{ii} | 4130.89 | 9.84 | 0.55 | ... | 110 (17) | 35 (8) |
| Si\textsc{ii} | 5055.98 | 10.07 | 0.52 | ... | 126 (27) | 53 (15) |
| Si\textsc{ii} | 6347.11 | 8.12 | -0.15 | ... | 220 (70) | 112 (22) |
| Si\textsc{ii} | 6371.37 | 8.12 | -0.08 | ... | 160 (20) | 45 (16) |
| Ca\textsc{i} | 4226.73 | 0.27 | 210 (60) | ... |
| Ca\textsc{ii} | 3158.87 | 3.12 | 0.24 | 2600 (520) | 890 (70) | 200 (20) |
| Ca\textsc{ii} | 3179.33 | 3.15 | 0.50 | 3600 (720)$^f$ - Ca\textsc{ii} 6400 | 1180 (150)$^f$ - Ca\textsc{ii} 6400 | 250 (30) |
| Ca\textsc{ii} | 3181.28 | 3.15 | -0.46 | In Ca 3179.33 | In Ca 3179.33 | 47 (18) |
| Ca\textsc{ii} | 3706.02 | 3.12 | -0.48 | 1100 (220) | 240 (40) | 45 (5) |
| Ca\textsc{ii} | 3736.90 | 3.15 | -0.17 | 1700 (340)$^f$ - Fe\textsc{iii} | 590 (50) | 113 (9) |
| Ca\textsc{ii} | 3933.66 | 0.10 | 39,000$^d$ | 4700 (500) | 1300 (150) |
| Ca\textsc{ii} | 3968.47 | 0.20 | In Ca 3933.66$^d$ | 2740 (360) | 790 (80) |
| Ca\textsc{ii} | 8498.02 | 1.69 | -1.42 | 1350 (400) | 570 (80) | ... |
| Ca\textsc{ii} | 8542.09 | 1.70 | -0.46 | 5000 (1500) | 2340 (320) | 780 (90) |
| Ca\textsc{ii} | 8662.14 | 1.69 | -0.72 | 4300 (1300) | 1720 (160) | 290 (90) |
| Sc\textsc{ii} | 3672.53 | 0.62 | 18 (5) | ... |
| Sc\textsc{ii} | 3613.83 | 0.02 | 27 (6) | <80 | ... |
| Sc\textsc{iii} | 3630.74 | 0.08 | In Fe 3631.46 | ... |
| Ti\textsc{ii} | 3148.04 | 0 | -1.22 | 29 (8) | ... |
| Ti\textsc{ii} | 3154.19 | 0.11 | -1.15 | In Fe I 3154.20 | ... |
| Ti\textsc{ii} | 3161.20 | 0.11 | -0.69 | 20 (4) | ... |
| Ti\textsc{ii} | 3167.77 | 0.12 | -0.55 | 41 (8) | ... |
| Ti\textsc{ii} | 3162.57 | 0.14 | -0.38 | 54 (11) | ... |
| Ti\textsc{ii} | 3168.52 | 0.15 | -0.20 | 190 (30)$^f$ - Fe\textsc{iii} | 25 (10) | ... |
| Ti\textsc{ii} | 3190.87 | 1.08 | 0.23 | 136 (27) | 37 (18) | ... |
| Ti\textsc{ii} | 3229.19 | 0 | -0.56 | 130 (50) | 36 (11) | ... |
| Ti\textsc{ii} | 3229.42 | 0.13 | -0.11 | In 3226 interval | ... |
| Ti\textsc{ii} | 3229.42 | 0.13 | -0.11 | In 3226 interval | ... |
| Ti\textsc{ii} | 3228.60 | 1.08 | -0.23 | In 3226 interval | ... |
| Ti\textsc{ii} | 3229.42 | 0.13 | -0.11 | In 3226 interval | ... |
| Ti\textsc{ii} | 3229.42 | 0.13 | -0.11 | In 3226 interval | ... |
| Ti\textsc{ii} | 3229.42 | 0.13 | -0.11 | In 3226 interval | ... |
| Ion  | λ (Å) | eV  | log g/f | Equivalent Width (mA) |
|------|-------|-----|---------|-----------------------|
| TiII | 3254.25 | 0.05 | −0.56 | 96 (19)              |
| TiII | 3261.58 | 1.89 | 0.53 | 190 (40)              |
| TiII | 3261.61 | 1.23 | 0.10 | In Ti II 3261.58     |
| TiII | 3271.65 | 1.24 | −0.28 | In Ti II 3272.07     |
| TiII | 3272.07 | 1.22 | −0.18 | 90 (20)              |
| TiII | 3278.29 | 1.23 | −0.32 | 30 (9)               |
| TiII | 3287.92 | 1.08 | −0.24 | 40 (12)              |
| TiII | 3282.33 | 1.22 | −0.33 | 36 (7)               |
| TiII | 3287.65 | 1.89 | 0.46 | 75 (15)              |
| TiII | 3318.02 | 0.12 | −1.04 | 19 (4)               |
| TiII | 3321.70 | 1.23 | −0.31 | 42 (8)               |
| TiII | 3322.93 | 0.15 | −0.10 | 230 (50)             |
| TiII | 3326.76 | 0.11 | −1.16 | 19 (4)               |
| TiII | 3329.45 | 0.14 | −0.26 | 148 (30)             |
| TiII | 3332.11 | 1.24 | −0.11 | 42 (8)               |
| TiII | 3335.19 | 0.12 | −0.42 | 128 (26)             |
| TiII | 3340.34 | 0.11 | −0.54 | 120 (24)             |
| TiII | 3341.87 | 0.57 | 0.35 | 330 (70)             |
| TiII | 3349.03 | 0.61 | 0.43 | 116 (14)             |
| TiII | 3349.40 | 0.05 | 0.53 | 1010 (200)           |
| TiII | 3361.21 | 0.03 | 0.43 | 770 (150)            |
| TiII | 3372.79 | 0.02 | 0.28 | 560 (110)            |
| TiII | 3380.28 | 0.05 | −0.62 | 120 (24)             |
| TiII | 3383.76 | 0.0 | 0.16 | 450 (90)             |
| TiII | 3387.83 | 0.03 | −0.41 | 127 (25)             |
| TiII | 3394.57 | 0.012 | −0.55 | 124 (25)             |
| TiII | 3444.31 | 0.15 | −0.65 | 54 (11)              |
| TiII | 3461.50 | 0.14 | −0.95 | 47 (9)               |
| TiII | 3477.18 | 0.12 | −0.96 | 32 (6)               |
| TiII | 3491.05 | 0.11 | −1.15 | 35 (10)              |
| TiII | 3504.89 | 1.89 | 0.39 | 80 (16)              |
| TiII | 3510.84 | 1.89 | 0.29 | 50 (10)              |
| TiII | 3535.41 | 2.06 | 0.03 | 30 (6)               |
| TiII | 3685.19 | 0.57 | −0.04 | In Ti II 3685.20     |
| TiII | 3685.20 | 0.61 | 0.13 | 380 (80)             |
| TiII | 3741.64 | 1.58 | −0.07 | 20 (4)               |
| TiII | 3759.29 | 0.61 | 0.28 | 700 (100)            |
| TiII | 3759.32 | 0.57 | 0.18 | 400 (100)            |
| TiII | 3900.54 | 1.13 | −0.20 | 31 (6)               |
| TiII | 4468.51 | 1.13 | −0.60 | 17 (5)               |
| TiII | 4549.62 | 1.58 | −0.11 | 36 (7)               |
| VII  | 3125.28 | 0.32 | 0.04 | In Cr II 3124.97     |
| VII  | 3267.69 | 1.07 | 0.28 | 17 (6)               |
| VII  | 3271.12 | 1.10 | 0.38 | In Ti II 3272.07     |
| VII  | 3276.12 | 1.13 | 0.49 | 11 (3)               |
| CrII | 3124.97 | 2.46 | 0.30 | 180 (20)             |
| CrII | 3128.69 | 2.43 | −0.54 | No data              |
| CrII | 3132.05 | 2.48 | 0.42 | No data              |
| CrII | 3136.68 | 2.46 | −0.45 | No data              |
| CrII | 3147.22 | 2.48 | −0.59 | No data              |
| CrII | 3180.69 | 2.54 | −0.32 | In Ca II 3179.33     |
| CrII | 3197.08 | 2.54 | −0.43 | In Ca II 3179.33     |
| CrII | 3209.18 | 2.54 | −0.56 | In Ca II 3179.33     |
| CrII | 3217.39 | 2.54 | −0.69 | In Ca II 3179.33     |
| CrII | 3339.79 | 2.43 | −0.89 | In Ca II 3179.33     |
| CrII | 3342.58 | 2.46 | −0.74 | In Ca II 3179.33     |
| CrII | 3358.49 | 2.46 | −0.59 | In Ca II 3179.33     |
| CrII | 3360.29 | 3.10 | −0.32 | In Ca II 3179.33     |
| CrII | 3368.04 | 2.48 | −0.09 | In Ca II 3179.33     |
| CrII | 3403.31 | 2.43 | −0.67 | In Ca II 3179.33     |
| CrII | 3408.76 | 2.48 | −0.39 | In Ca II 3179.33     |
| CrII | 3421.20 | 2.42 | −0.71 | In Ca II 3179.33     |
| CrII | 3422.73 | 2.46 | −0.41 | In Ca II 3179.33     |
| CrII | 3433.29 | 2.43 | −0.73 | In Ca II 3179.33     |
### Table 2
(Continued)

| Ion   | \( \lambda \) | \( \chi \) | \( \log gf \) | Equivalent Width (mA) |
|-------|----------------|----------|---------------|------------------------|
|       | (Å)            | (eV)     |               | PG1225–079             |
| Mn \( \Pi \) | 3441.99       | 1.78     | −0.36         | 21 (8)                 |
| Mn \( \Pi \) | 3460.31       | 1.81     | −0.64         | 30 (9)                 |
| Mn \( \Pi \) | 3474.04       | 1.81     | −0.93         | In Mn \( \Pi \) 3474.13 |
| Mn \( \Pi \) | 3474.13       | 1.83     | −1.06         | In Mn \( \Pi \) 3474.13 |
| Fe \( \Pi \) | 3440.61       | 0        | −0.67         | 39 (8) \( \gamma \rightarrow \text{Fe} \) |
| Fe \( \Pi \) | 3440.99       | 0.05     | −0.96         | In Fe \( \Pi \) 3440.61 |
| Fe \( \Pi \) | 3490.57       | 0.05     | −1.10         | In Ti \( \Pi \) 3491.05 |
| Fe \( \Pi \) | 3565.38       | 0.96     | −0.13         | 59 (12)                |
| Fe \( \Pi \) | 3570.10       | 0.92     | 0.15          | 127 (25)               |
| Fe \( \Pi \) | 3581.19       | 0.86     | 0.41          | 280 (60)               |
| Fe \( \Pi \) | 3608.86       | 1.01     | −0.10         | 40 (8)                 |
| Fe \( \Pi \) | 3618.77       | 0.99     | −0.00         | 87 (20) \( \gamma \rightarrow \text{Ni} \) |
| Fe \( \Pi \) | 3631.46       | 0.96     | −0.04         | 100 (20) \( \gamma \rightarrow \text{Sc} \) |
| Fe \( \Pi \) | 3719.93       | 0        | −0.43         | 108 (22)               |
| Fe \( \Pi \) | 3734.86       | 0.86     | 0.32          | In Ca \( \Pi \) 3737   |
| Fe \( \Pi \) | 3737.13       | 0.05     | −0.57         | In Ca \( \Pi \) 3737   |
| Fe \( \Pi \) | 3745.56       | 0.09     | −0.77         | 32 (6)                 |
| Fe \( \Pi \) | 3749.49       | 0.92     | 0.16          | 133 (27)               |
| Fe \( \Pi \) | 3758.23       | 0.96     | −0.03         | In Fe \( \Pi \) 3759.29 |
| Fe \( \Pi \) | 3763.79       | 0.99     | −0.24         | In Fe \( \Pi \) 3761.32 |
| Fe \( \Pi \) | 3815.84       | 1.49     | 0.24          | 47 (9)                 |
| Fe \( \Pi \) | 3820.43       | 0.86     | 0.12          | 130 (26)               |
| Fe \( \Pi \) | 3825.88       | 0.92     | −0.04         | 52 (10)                |
| Fe \( \Pi \) | 3827.82       | 1.56     | 0.06          | In 3827 interval       |
| Fe \( \Pi \) | 3834.22       | 0.96     | −0.30         | In 3827 interval       |
| Fe \( \Pi \) | 3840.44       | 0.99     | −0.51         | In 3827 interval       |
| Fe \( \Pi \) | 3856.37       | 0.05     | −1.29         | 32 (6)                 |
| Fe \( \Pi \) | 3859.91       | 0        | −0.71         | 58 (12)                |
| Fe \( \Pi \) | 4383.54       | 1.49     | 0.20          | 37 (8)                 |
| Fe \( \Pi \) | 3154.20       | 3.77     | −0.51         | 48 (10) \( \gamma \rightarrow \text{Ti} \) |
| Fe \( \Pi \) | 3167.86       | 3.81     | −0.72         | In Ti \( \Pi \) 3168.5 |
| Fe \( \Pi \) | 3177.53       | 3.90     | −0.90         | 100 (16)               |
| Fe \( \Pi \) | 3183.11       | 1.70     | −2.20         | 94 (46)                |
| Fe \( \Pi \) | 3186.74       | 1.70     | −1.77         | 57 (11)                |
| Fe \( \Pi \) | 3192.91       | 1.67     | −2.01         | 30 (6)                 |
| Fe \( \Pi \) | 3193.80       | 1.72     | −1.78         | 60 (12) \( \gamma \rightarrow \text{Fe} \) |
| Fe \( \Pi \) | 3193.86       | 3.81     | −1.44         | In Fe \( \Pi \) 3193.80 |
| Fe \( \Pi \) | 3198.87       | 1.67     | −1.87         | 75 (15)                |
| Fe \( \Pi \) | 3210.44       | 1.72     | −1.76         | 43 (9)                 |
| Fe \( \Pi \) | 3213.31       | 1.70     | −1.39         | 170 (30)               |
| Fe \( \Pi \) | 3227.74       | 1.67     | −1.18         | 300 (50)               |
| Fe \( \Pi \) | 3237.82       | 3.89     | −1.37         | 22 (6)                 |
| Fe \( \Pi \) | 3243.72       | 4.15     | −1.19         | 49 (17)                |
| Fe \( \Pi \) | 3247.18       | 3.89     | −1.17         | 15 (5)                 |
| Fe \( \Pi \) | 3255.89       | 0.99     | −2.56         | 20 (6)                 |
| Fe \( \Pi \) | 3258.77       | 3.89     | −1.15         | 10 (3)                 |
| Fe \( \Pi \) | 3259.05       | 3.90     | −0.97         | 16 (5)                 |
| Fe \( \Pi \) | 3277.35       | 0.99     | −2.39         | 20 (6)                 |
| Fe \( \Pi \) | 3281.29       | 1.04     | −2.74         | 13 (4)                 |
| Fe \( \Pi \) | 3295.03       | 3.81     | −1.57         | 24 (10)                |
| Fe \( \Pi \) | 3323.06       | 3.97     | −1.62         | In Ti \( \Pi \) 3322.93 |
| Fe \( \Pi \) | 4178.86       | 2.58     | −2.51         | 21 (9)                 |
| Fe \( \Pi \) | 4233.17       | 2.58     | −1.97         | 59 (18)                |
| Fe \( \Pi \) | 4351.77       | 2.70     | −2.25         | 31 (7)                 |
| Fe \( \Pi \) | 4522.63       | 2.84     | −2.25         | 28 (10)                |
| Fe \( \Pi \) | 4549.47       | 2.83     | −2.09         | 55 (17)                |
| Fe \( \Pi \) | 4583.84       | 2.81     | −1.93         | 50 (13)                |
| Fe \( \Pi \) | 4923.93       | 2.89     | −1.26         | 68 (14)                |
| Fe \( \Pi \) | 5018.44       | 2.89     | −1.10         | 90 (18)                |
| Fe \( \Pi \) | 5169.03       | 2.89     | −1.00         | 113 (45)               |
| Fe \( \Pi \) | 5234.62       | 3.22     | −2.18         | 30 (5)                 |
| Ni \( \Pi \) | 5316.61       | 3.15     | −1.87         | 70 (29)                |
| Ni \( \Pi \) | 3414.76       | 0.03     | −0.014        | 30 (12)                |
| Ni \( \Pi \) | 3524.53       | 0.03     | 0.008         | 40 (16)                |
Table 2
(Continued)

| Ion    | λ\(^a\) \(\text{Å}\) | χ \(\text{eV}\) | log \(gf\) | Equivalent Width (mÅ) |
|--------|----------------------|-----------|-----------|----------------------|
|        | PG1225−079           | HS2253+8023 | G241-6\(^b\) |
| Ni i   | 3619.39              | 0.42      | 0.04      | In Fe i 3618.77       |
| Ni ii  | 3513.99              | 2.87      | −1.46     | ...                  |
| Sr ii  | 4077.71              | 0         | 0.17      | <60                  |
| Interval | 3226−3221          | ...       | ...       | 450 (500) \(^{−}\) Fe ii Ti ii |
| Interval | 3800−3850          | ...       | ...       | 2,100 (400) \(^{−}\) Mg i Fe i |

Notes.
\(^a\) Laboratory wavelength in air. Wavelength, χ (excitation energy of lower state) and log \(gf\) data from the Vienna Atomic Line Database.

\(^b\) G241-6 abundances from Zuckerman et al. (2010) are associated with the EWs of this table. Spectra of G241-6 are shown in Figure 13 of this paper and Figure 4 of Zuckerman et al. (2010).

\(^c\) Blended line—contributing element noted in italic with line data given in the table. The equivalent width is from the total summed flux of the blend.

\(^d\) Combined Ca H&K EW measurement of 39,000 mÅ from Koester et al. (2005b) is used since the HIRES data do not fully cover the red wing of this large feature.

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Figure 4. Portion of the HIRES data (black) of HS2253+8023, smoothed with a five-point boxcar average and displaying lines of He i, Ca ii, Cr ii, and Fe ii. Wavelengths are in air and a heliocentric rest frame. A \(T_{\text{eff}}\) = 14,400 K, log \(g\) = 8.4 model, convolved with a Gaussian to approximate the instrumental resolution and with element abundances from Table 4, is plotted in red.

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

Figure 5. HS2253+8023. Similar to Figure 4, but for Mg i, Si ii, and Fe i. This portion of the data was smoothed with a three-point boxcar average.

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

Figure 6. HS2253+8023. Similar to Figure 4, but for O i. This portion of the data was smoothed with a five-point boxcar average.

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

Figure 7. HS2253+8023. Similar to Figure 4, but displaying lines of Ti ii, Cr ii, Mn ii, and a marginal detection of Ni ii.

(A color version of this figure is available in the online journal.)
separate (February 13, 14) exposures covering the Ca H&K region of PG1225, with no noticeable variations between exposures. The observed Ca II infrared triplet of PG1225 does not appear to display any emission features. Emission cores have been seen in Hα of hydrogen-dominated WDs hotter than 25,000 K and are understood to arise from non-local thermodynamic equilibrium (NLTE) effects. The one HIRES exposure covering Hα in PG1225, obtained on February 26, does not display clear Hα core emission with a continuum S/N ~50 near 6650 Å. Still, NLTE effects could conceivably cause emission in the strong Ca H&K lines since the cores are formed high up in the atmosphere, while the relatively weaker Hα line of PG1225 is likely formed at a deeper location. Alternatively, Ca H&K emission cores, as well as Hα core emission, are well-known signatures of chromospheric activity in main-sequence stars; further discussion of chromospheric activity in a WD is beyond the scope of this work (see Musielak et al. 2005).

One more spectroscopic peculiarity we point out is the presence of a narrow absorption core component at the line center of He I λ5876 in PG1225 (Figures 8 and 16), as well as in GD362 and GD16 (≡ HS 0146+1847) shown in Figure 16. These three WDs have helium-dominated atmospheres, with effective temperatures in the range 10,500 K–11,500 K; they all have detected circumstellar dust (Becklin et al. 2005; Kilic et al. 2005; Farihi et al. 2009), heavy atmospheric pollution (Koester et al. 2005a; Zuckerman et al. 2007), and possess relatively large amounts of hydrogen in their convective envelopes. Two possibly analogous, but weakly detected, features in PG1225 are narrow absorption lines instead of broad ones centered on He I λ3889 and He I λ4472, with the latter shown in Figure 8. The He I λ5876 core feature was first discovered in HIRES data of GD362 by Zuckerman et al. (2007) and noted again by Tremblay et al. (2010); we now see it in HIRES spectra of GD16 and PG1225 as well. Zuckerman et al. (2007) suggested that NLTE effects, similar to those seen in the cores of Hα lines...
in hydrogen-dominated WDs, could be present. The exact origin of the He core feature is not known at this time and we do not discuss it further in this paper.

3. MODEL ATMOSPHERES

The model input physics is described by Koester (2010) with all absorption line data taken from the Vienna Atomic Line Database (VALD). Key input parameters are the effective temperature, $T_{\text{eff}}$, surface gravity, $g$, and the atmospheric abundances of elements relative to the dominant constituent, helium in the current study. In the range of temperatures considered here, helium is mostly neutral, and the high-Z elements and hydrogen are significant contributors of electrons in the atmosphere. Thus, we calculated and analyzed our models with hydrogen and high-Z elements in a self-consistent way, and included Earth-like abundances for undetected but expected el-

![Figure 11. PG1225−079. Similar to Figure 9, but for V and Ni. The data in the lower panel are smoothed by a three-point boxcar average.](image)

![Figure 12. PG1225−079. Similar to Figure 9, but smoothed by a three-point (upper panel) and five-point (lower panel) boxcar average, and displaying Sc Ti and Fe i lines; a probable blend of a Ni i feature is also labeled. The apparent “mis-fit” of some Fe i lines is due to a combination of the ~0.1 dex discrepancy of Fe i and Fe ii abundances, uncertainties in the modeled line data, and an unmodeled shift of Fe i features (see also Figure 14).](image)

![Figure 13. Unsmoothed portions of the combined HIRES spectrum of G241-6 are plotted in black, displaying Fe ii, Mg i, Si ii, and He i lines. Wavelengths are in air and a heliocentric rest frame. Plotted in red is a $T_{\text{eff}} = 15,300$ K, log $g = 8.0$ model, convolved with a Gaussian to approximate the instrumental resolution, and with element abundances from Zuckerman et al. (2010); the model is blue shifted by $-28.0$ km s$^{-1}$, the mean velocity from the full set of measured absorption lines. See also Figure 4 of Zuckerman et al. (2010) for a display of O i lines in G241-6.](image)

![Figure 14. Histograms of (heliocentric) velocity measurements from HIRES data. The velocity bin size is 0.5 km s$^{-1}$ for PG1225 and 1 km s$^{-1}$ for HS2253; the larger velocity dispersion for the latter star is likely due to the lower S/N. Fe i lines are a distinguished set in PG1225, whereas the eight Fe i lines in HS2253+8023 span between $-3$ km s$^{-1}$ and $+12$ km s$^{-1}$.](image)
and abundance estimates that derive from (1) photometric fitting of the spectral energy distribution (SED), preferably using UV to optical and infrared wavelengths, (2) fitting the hydrogen and helium lines in profile and/or strength, and (3) demanding a balance in the abundances that come from different ionization states of the same element. In principle, the model would meet the requirements of (1) through (3) while also achieving a reasonable fit of the broadening and symmetry of heavy element lines—in practice, it can be challenging to reconcile all these points, but we find reasonable consistency for the WDs studied here. Precise parameters are not required for our abundance analysis, since we are interested in the pollutant-to-pollutant ratios, which are relatively insensitive to the particular model (Klein et al. 2010; also Section 4 of the present paper).

In the analysis of helium-dominated atmospheres with effective temperature below \( \sim 16,000 \) K, we must deal with the difficulty that the parameters, \( T_{\text{eff}} \) and gravity, \( g \), are effectively coupled, such that \( T_{\text{eff}}/\log g \) fits to the helium lines are not unique. This has led many authors (present authors included) to set \( \log g \) to the average value of 8.0, so that one may proceed with a fit to the temperature. In the current analysis we took a different approach, similar to Dufour et al. (2010), who found that a larger than average gravity was required to fit simultaneously the features from two ionization states, Mg\( i \) and Mg\( ii \), in the extremely polluted helium-rich WD, SDSS J073842.56+183509.6 (hereafter SDSS0738). For each star in the present study we allow for a departure from \( \log g = 8.0 \), and instead work with a set of three \( T_{\text{eff}}/\log g \) solutions for \( T_{\text{eff}} \) and \( \log g \) which do a reasonably good job of satisfying the SED, He\( i \) line strengths, and the ionization balance between neutral and singly ionized species of Fe, Mg, and Ca. The model parameters used are listed in Table 3 and span a range of \( \pm 300 \) or 400 K for effective
As Limoges & Bergeron (2010) pointed out, the strengths of He\textsc{i} use of He\textsc{ii} some He\textsc{ii} photometry, are in agreement with the T\textsubscript{eff} results.

Figure 17. Portions of the spectral energy distributions (SED) of PG1225-079 (top) and HS2253+8023 (bottom) displaying archival IUE spectra (black, solid line) and GALEX photometry (yellow boxes). The models are convolved with 6 Å Gaussians and scaled to match visual photometry. For PG1225-079 the 10,500 K model is a red, dashed line, and the 11,100 K model is a green, dotted line. For HS2253+8023 the 14,000 K model is a red, dashed line, and the 14,800 K model is a green, dotted line. An extensive list of UV absorption lines is included in the models, with element abundances from the current HIRES measurements (Tables 4 and 5) and carbon from previous UV analyses (Friedrich et al. 1999; Wolff et al. 2002). In both cases the lower temperature model fits the SED well, but if there is some unaccounted-for extinction, then the higher temperature model may be appropriate.

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

temperature and \( \pm 0.3 \) dex for log g. An additional constraint on the gravity could come from a sufficiently precise parallax measurement—e.g., as Kilic et al. (2008b) carried out for GD362—and help narrow the range of possible log g and T\textsubscript{eff} values. To our knowledge, PG1225-079 and HS2253+8023 do not have reported parallaxes at this time.

3.1. HS2253+8023 T\textsubscript{eff}/log g

The SEDs of our current models for HS2253 in the range T\textsubscript{eff} = 14000–14800 K, scaled to Two Micron All Sky Survey (2MASS) photometry, are in agreement with the IUE data and Galaxy Evolution Explorer (GALEX) photometry (Figure 17). As Limoges & Bergeron (2010) pointed out, the strengths of some He\textsc{i} lines are especially gravity sensitive, and we make use of He\textsc{i} \( \lambda 3820, \lambda 4388, \lambda 4713, \) and \( \lambda 4922 \) in that regard. We find the set of models T\textsubscript{eff}/log g = 14000/8.1, 14400/8.4, and 14800/8.7 all give reasonable and roughly similar fits for most of the He\textsc{i} lines, shown plotted by the red line in Figure 2. It turns out that the overprediction of He\textsc{i} \( \lambda 4713 \) mentioned by Friedrich et al. (1999) is resolved by our use of higher than average gravity, although there remains an unaccounted-for shift of that line’s center (top panel Figure 2).

When we use log g = 8.0, the model profiles are too deep and too narrow for almost all lines of most elements. Having worked with matching similar models to similar HIRES observations of similar WDs (GD40 and G241-6), we presume that a mismatch in high-Z line broadening between the data and instrument-convolved model is not a problem of accounting for the instrumental broadening, but rather is an indication that there is some intrinsic broadening needed in the model, such as a higher gravity. We found that the models listed in Table 3 produced better overall fits to the high-Z line profiles than models of average gravity. Similarly, the fit to the H\alpha profile (Figure 3) is better with higher gravity.

Finally, with our Table 3 models, the ionization balance for abundances of Mg and Fe naturally comes out of the analysis of HS2253 at our desired consistency of within 0.1 dex between abundances from neutral and singly ionized states (Table 4). Obtaining agreement in the ionization balance has proven challenging in other stars, including GD362, GD40, and PG1225 as described below.

3.2. PG1225-079 T\textsubscript{eff}/log g

At temperatures \(< 12,000 \) K, the optical He\textsc{i} lines begin to disappear; He\textsc{i} \( \lambda 5876 \) (Figure 8) is the strongest line observed. In this range of T\textsubscript{eff}, only a very small fraction of the photospheric helium is involved in the formation of optical helium lines, since they arise from levels of high excitation energy, e.g., 20.9 eV above ground. Small changes in the atmosphere may have a large impact on the He line appearance, and we know that there is some unmodeled activity in the upper atmosphere of PG1225 as is apparent from the emission cores of the Ca\textsc{ii} H\&K lines (Figure 15) and the narrow core of He\textsc{i} \( \lambda 5876 \) (Figures 8 and 16). For the discussion of atmospheric parameters that follows, we ignore the narrow core of the He\textsc{i} \( \lambda 5876 \) feature described in Section 2 and only consider the broad component of He\textsc{i} \( \lambda 5876 \).

The SEDs of our current models for PG1225, scaled to 2MASS photometry, are in good agreement with the IUE spectrum and GALEX photometry (upper panel Figure 17) for T\textsubscript{eff} near 10,500 K as used in previous work by Wolff et al. (2002) with log g = 8.0. However, looking at the ionization balance, a 10500/8.0 model results in a 0.2 dex difference between iron abundances derived from Fe\textsc{i} and Fe\textsc{ii}. This is in the sense that Fe\textsc{i} lines are overpredicted and the discrepancy increases to 0.4 dex with a higher gravity model at 10500/8.3. Inversely, we find at T\textsubscript{eff} = 10,500 K that the two states of Fe are brought into marginal agreement (within 0.03 dex uncertainties—Table 5) by lowering the gravity to log g = 7.7. At this point in the T\textsubscript{eff}/log g parameter space, the 10,500/7.7 model produces a He\textsc{i} \( \lambda 5876 \) line with a predicted EW that matches the measured value at 1.5 Å, but the predicted profile is somewhat narrower and deeper than observed (red curve in Figure 8). Also, the He\textsc{i} \( \lambda 4472 \) line is not matched. The model helium lines can be made shallower by increasing the gravity or decreasing the temperature, but always at the expense of degrading the ionization balance and the EW fit. As was the case for HS2253, there is a degeneracy of model solutions that fit the EW of the helium line—for example, 10,500/7.7, 10,800/8.0, and 11,100/8.3 all produce a similar strength (and depth) He\textsc{i} \( \lambda 5876 \) feature. Accepting the imperfections in the helium line profile fitting, we favor these models as our best compromise since they (1) are in reasonable

\footnote{While G241-6 does have a parallax measurement (van Altena et al. 1995), it is not precise enough to improve on the spectroscopically assumed T\textsubscript{eff}/log g used by Zuckerman et al. (2010).}
agreement with the UV/optical/IR SED, (2) fit the He\textsc{i} $\lambda$5876 EW, and (3) support Fe\textsc{i}/Fe\textsc{ii} abundance agreement to within 0.15 dex. We use this set of three models for establishing pollutant-to-pollutant abundance ratios which, as we show in Section 4, are not very sensitive to the particular choice of model.

### Table 4

| Z     | HS2253+8023 | 14000/8.1 | 14400/8.4 | 14800/8.7 | 14400/8.1 | 14400/8.4 | 14800/8.7 |
|-------|-------------|-----------|-----------|-----------|-----------|-----------|-----------|
|       | log(Z/He)   | log(Z/He) | log(Z/He) | log(t/yr) | log(t/yr) | log(t/yr) |
| H     | -5.70 (0.06) | -5.62 (0.06) | -5.55 (0.06) | ... | ... | ... |
| O     | -5.48 (0.07) | -5.37 (0.07) | -5.28 (0.07) | 5.71 | 5.01 | 4.31 |
| Mg    | -6.23 (0.06) | -6.10 (0.04) | -6.02 (0.03) | 5.63 | 4.93 | 4.23 |
| Si    | -6.27 (0.05) | -6.12 (0.06) | -5.03 (0.04) | ... | ... | ... |
| Ca    | -6.40 (0.03) | -6.27 (0.03) | -6.16 (0.04) | 5.63 | 4.93 | 4.21 |
| Ti    | -7.10 (0.03) | -6.99 (0.03) | -6.92 (0.05) | 5.50 | 4.78 | 4.06 |
| Cr    | -8.92 (0.02) | -8.74 (0.02) | -8.55 (0.02) | 5.43 | 4.73 | 4.03 |
| Mn    | -8.63 (0.09) | -8.42 (0.10) | -8.24 (0.09) | 5.43 | 4.71 | 3.99 |
| Fe    | -6.34 (0.04) | -6.17 (0.03) | -6.00 (0.02) | 5.42 | 4.71 | 3.98 |
| Ni    | -7.51 :     | -7.31 :     | -7.14 :     | 5.40 | 4.68 | 3.96 |
| C     | ...         | ...         | ...         | 5.74 | 5.05 | 4.35 |
| Na    | ...         | -6.8       | ...         | 5.63 | 4.92 | 4.21 |
| Mg    | ...         | -6.7       | ...         | 5.61 | 4.92 | 4.22 |
| Ca    | ...         | -8.9       | ...         | 5.45 | 4.74 | 4.03 |
| V     | ...         | <8.6       | ...         | 5.42 | 4.73 | 4.02 |
| Sr    | ...         | <9.6       | ...         | 5.24 | 4.53 | 3.81 |

**Notes.** Element abundances and settling times derived from the equivalent width measurements of Table 2 and different models, as described in Sections 3, 4, and 5. Uncertainties in parentheses are either the standard deviation of the mean for the set of individual line abundances, or the propagated measurement error, whichever is greater. When a significant difference is measured between ionization states of an element (only true for iron), this additional uncertainty is added in. While the absolute abundances and diffusion times vary considerably between models, the relative abundances and relative diffusion times among the listed elements are far less sensitive to changes in the model.

### Table 5

| Z       | PG1225—079 | 10500/7.7 | 10800/8.0 | 11100/8.3 | 10500/7.7 | 10800/8.0 | 11100/8.3 |
|---------|-------------|-----------|-----------|-----------|-----------|-----------|-----------|
|         | log(Z/He)   | log(Z/He) | log(Z/He) | log(t/yr) | log(t/yr) | log(t/yr) |
| H       | -4.13 (0.10) | -4.05 (0.10) | -3.99 (0.10) | ... | ... | ... |
| Mg      | -7.44 (0.05) | -7.27 (0.05) | -7.11 (0.05) | 6.85 | 6.14 | 5.41 |
| From Mg\textsc{i} | -7.44 (0.06) | -7.27 (0.06) | -7.11 (0.06) | ... | ... | ... |
| From Mg\textsc{ii} | -7.43 (0.10) | -7.30 (0.10) | -7.11 (0.10) | ... | ... | ... |
| Ca      | -8.25 (0.03) | -8.06 (0.03) | -7.90 (0.04) | 6.83 | 6.07 | 5.32 |
| From Ca\textsc{i} | -8.30 (0.15) | -8.18 (0.15) | -8.04 (0.15) | ... | ... | ... |
| From Ca\textsc{ii} | -8.24 (0.03) | -8.04 (0.03) | -7.89 (0.04) | ... | ... | ... |
| Sc      | -11.57 (0.07) | -11.29 (0.07) | -11.05 (0.07) | 6.78 | 6.03 | 5.28 |
| Ti      | -9.68 (0.02) | -9.45 (0.02) | -9.23 (0.02) | 6.76 | 6.01 | 5.26 |
| V       | -10.68 (0.10) | -10.41 (0.10) | -10.18 (0.10) | 6.73 | 5.98 | 5.23 |
| Cr      | -9.47 (0.06) | -9.27 (0.06) | -9.05 (0.06) | 6.72 | 5.97 | 5.24 |
| Mn      | -10.03 (0.14) | -9.79 (0.14) | -9.52 (0.14) | 6.70 | 5.96 | 5.24 |
| Fe      | -7.64 (0.03) | -7.42 (0.07) | -7.21 (0.08) | 6.69 | 5.97 | 5.25 |
| From Fe\textsc{i} | -7.67 (0.03) | -7.50 (0.03) | -7.30 (0.03) | ... | ... | ... |
| From Fe\textsc{ii} | -7.62 (0.03) | -7.36 (0.03) | -7.15 (0.03) | ... | ... | ... |
| Ni      | -8.88 (0.14) | -8.76 (0.14) | -8.64 (0.14) | 6.70 | 5.99 | 5.24 |
| C       | ...         | ...         | ...         | 6.89 | 6.18 | 5.47 |
| O       | <8.69       | <8.54       | <8.44       | 6.86 | 6.15 | 5.43 |
| Na      | <8.45       | <8.26       | <8.02       | 6.83 | 6.12 | 5.41 |
| Al      | <8.04       | <7.84       | <7.68       | 6.84 | 6.11 | 5.38 |
| Si      | <7.49       | <7.27       | <7.07       | 6.85 | 6.11 | 5.39 |
| Sr      | <11.90      | <11.65      | <11.38      | 6.56 | 5.85 | 5.10 |

**Notes.** Similar to Table 4, but for PG1225—079.

4. ABUNDANCES

Abundances are calculated for each line by linearly scaling the model input abundance by the ratio of EWs measured in the observed spectrum (Table 2) to that of the model. In cases of blended features or otherwise noisy regions, a visual inspection of the profile fit aids the determinations. For each element we use
the average of the set of calculated line abundances as the input for the next iteration of the model. It takes a few iterations until the average converges. Abundances derived from individual lines are given equal weight in the final average element abundance. The EW measurement uncertainties are propagated through to an uncertainty in the final average abundance. We compare that to the mean deviation for the set of lines of an element and assume the larger error.

A challenge to abundance accuracy can come from discrepancies in the atomic line data and broadening parameters (Vennes et al. 2011). However, with multiple lines of each element observed, biases due to errors in the atomic data are minimized. We typically find a low dispersion in derived abundances for elements with multiple line detections (ranging from 0.02 to 0.15 dex)—generally comparable to, or smaller than, the propagated measurement uncertainties—suggesting that the errors due to line data (including broadening parameters) are not a big factor in the current results.

Tables 4 and 5 list the pollutant abundances relative to helium, derived from the different models considered for each star. This explicitly shows that the choice of model temperature and gravity is a significant source of systematic uncertainty in absolute abundance determinations. The absolute (pollutant-to-helium) abundances vary by 0.2–0.4 dex with the modest in absolute abundance determinations. The absolute (pollutant-to-pollutant) element abundances are relatively homologous from one model to another with ratios varying only ∼40% or less, a comparable contribution to the uncertainty as from the propagated measurement error. The upshot is that the relative composition of the polluting elements can be measured to a precision better than that of the absolute mass, or rate, of material accreted. The relative element abundances with respect to the fiducial—magnesium—are given in Table 6.

Comparisons of abundances with prior work are possible for H, Mg, Si, Ca, and Fe, although previous uncertainties are typically large (0.2–0.7 dex), and tend to propagate to a sizable range for the abundance ratios. For PG1225, the HIRES abundances relative to helium are nearly all within the uncertainties of those quoted by Wolff et al. (2002). Within the uncertainty limits, pollutant-to-pollutant ratios agree between previous and present analyses. From the HIRES data of PG1225, we obtain abundances for H, Mg, Ca, Sc, Ti, V, Cr, Mn, Fe, and Ni, and upper limits on O, Na, Al, and Sr, with an upper limit for Si that is consistent with its UV detection and analysis (Wolff et al. 2002); an upper limit for carbon is taken from the UV work (Friedrich et al. 1999).

5. ACCRETION–DIFFUSION MODELS

As mentioned in Section 1, a helium-dominated polluted WD system has an evolving interplay of accretion and diffusion, since these WDs have relatively long settling times. Calculated settling times specific to our particular models of HS2253 and PG1225 for the various elements studied are given in Tables 4 and 5. As described in Koester (2009), the accretion–diffusion situation is roughly categorized by three phases: (1) an early phase in which accretion began “recently,” that is, before differential settling has had time to significantly alter the abundance ratios—the observed atmospheric abundances directly represent the accreted ones; (2) a steady state with ongoing accretion, where the observed abundances are related to the accreted ones by ratios of settling times; and (3) a dissipation phase after accretion has slowed, paused, or ended, and elements with shorter settling times disappear faster than those with longer settling times. We use these benchmarks to characterize our observations.

If accretion has been going on longer than a couple of settling times, then a steady-state interpretation may be appropriate. This assumes a semi-continuous flow of material lasting for ∼1 Myr or more in the systems under study here. To calculate the steady-state abundances, for each element we take the average over different models of the ratios of settling times and use the average ratios to apply a differential settling “correction” to the abundance ratios of Table 6 as prescribed by Equation (7) of Koester (2009). It is worth noting that analogous to the abundances, while the settling times themselves vary significantly from one model to another, the pollutant-to-pollutant ratios of settling times vary very little (rms of most <3%, all <8%) with the model variations for a given source. For each element, the rms’s of diffusion data among models

| Z/Mg | PG1225−079 Convective Zone | HS2253+8023 Convective Zone | Solar (lodders 2003) |
|------|---------------------------|----------------------------|---------------------|
| H/Mg | 1700 (500)                | 3.1(0.6)                   | 2.8 × 10^3          |
| C/Mg | < 5a                      | <0.01b                     | 6.9                 |
| O/Mg | <50                       | 5.4(1.1)                   | 14                  |
| Na/Mg| <0.12                     | <0.22                      | 0.056               |
| Al/Mg| <0.31                     | <0.30                      | 0.081               |
| Si/Mg| <1.1                      | 0.68(0.10)                 | 0.98                |
| Ca/Mg| 0.16 (0.02)               | 0.13(0.02)                 | 0.062               |
| Sc/Mg| 9.4 ± 2.7 × 10^−5         | <2.2 × 10^−4               | 3.3 × 10^−5         |
| Ti/Mg| 6.7 ± 1.2 × 10^−3         | 2.4 ± 0.6 × 10^−3          | 2.3 × 10^−3         |
| V/Mg | 7.1 ± 2.2 × 10^−4         | <3.7 × 10^−3               | 2.8 × 10^−4         |
| Cr/Mg| 0.010 (0.002)             | 0.013(0.003)               | 0.013               |
| Mn/Mg| 3.1 ± 1.2 × 10^−3         | 5.1 ± 1.7 × 10^−3          | 8.9 × 10^−3         |
| Fe/Mg| 0.71 (0.12)               | 0.89(0.18)                 | 0.83                |
| Ni/Mg| 0.033 (0.011)             | 0.06                       | 0.047               |
| Sr/Mg| <4.5 × 10^−5              | <3.1 × 10^−4               | 2.3 × 10^−5         |

Notes. Measured atmospheric abundance ratios calculated as the average of three models with ratios from Tables 4 and 5. Uncertainties in parentheses are a combination of the propagated abundance ratio measurement uncertainties and the root-mean-square of ratio values from different models from Tables 4 and 5, added in quadrature.

a C/Mg from Wolff et al. (2002).

b C/Mg from Friedrich et al. (1999).
Figure 18. Parent body abundance ratios from Table 6, with values for Earth from Allègre et al. (2001) and settling times from Tables 4 and 5; 50% condensation temperatures are from Lodders (2003). The fiducial element, Mg, has a 50% \( T_c = 1336 \, \text{K} \), nearly the same as that of Fe. Oxygen is off the plot at 50% \( T_c = 180 \, \text{K} \). The dotted line at ordinate value 1 is to guide the eye to Earth-like values.

are propagated in quadrature into the steady-state abundance uncertainties.

The principle result of applying a steady-state “correction” is an increase in the abundance of iron and other heavy elements relative to the lighter elements in the inferred parent body. This effect is apparent in Figure 18 where the early-phase (= convective zone = CVZ) abundances are plotted as filled markers, while the open markers represent parent body abundances for the system in a steady state. For the set of elements plotted in Figure 18, Mg and Si are the lightest and have the longest settling times. Since Mg is the fiducial, applying a settling “correction” moves all the points of the plot up, relative to Mg, as seen in going from early-phase to steady-state values. The difference between an early-phase and a steady-state interpretation is most pronounced in the O/Fe ratio, which can be seen by comparison of the bulk composition bar graphs, Figures 19 and 20.

6. RESULTS AND DISCUSSION

From Table 6 we find that the accreted abundances are not in solar proportions for the volatiles H, C, and O (HS2253), verifying that these systems are neither accreting from the interstellar medium nor gas giant planets. Rather, for example, the distinctively low carbon abundances in both HS2253 and GD40 are such that C/Mg is more than an order of magnitude below the solar abundance and therefore more similar to Earth (Jura 2006). It is helpful to compare all measurements to a set of values such as the bulk Earth. In the following we will discuss the abundance ratios of Table 6, mainly through Figure 18, in which the observed abundance ratios are normalized to Mg and the bulk Earth, and Figures 19 and 20 in which we compare the major element compositions of inferred parent bodies with the bulk Earth.

HS2253 and PG1225 each have the high-Z mass of a large asteroid \( \sim 10^{22} \, \text{g} \) currently in their convective zones (Table 3)—similar to GD362 (Zuckerman et al. 2007) and GD40 (Klein et al. 2010). HS2253 has one of the highest time-averaged mass accretion rates of all polluted WDs, being comparable to GD362 (Jura et al. 2009; Koester 2009) at \( \sim 10^{10} \, \text{g} \, \text{s}^{-1} \), with SDSS0738 apparently being the current
champion at $\sim 10^{11}$ g s$^{-1}$ based on Dufour et al. (2010) and our settling time calculations parallel to Koester (2009). The time-averaged mass accretion rate of rocky material in PG1225 is a few $\times 10^8$ g s$^{-1}$, about a factor of 5–10 less than GD40.

6.1. HS2253+8023 Composition

If a WD accretes a rocky planetary body, then the relative element abundances will have the distinctive proportions that arise from mineral oxides (Jura et al. 2009; Klein et al. 2010), made up of MgO, Al$_2$O$_3$, SiO$_2$, CaO, TiO, Cr$_2$O$_3$, etc., with iron coming from either FeO, Fe$_2$O$_3$, or Fe metal if a differentiated core formed. Another possible vehicle for oxygen in a terrestrial-type planetary body is water ice, which depends on how much hydrogen is present. For HS2253, the HIRES measurement of oxygen plus all major elements, some minor ones, and hydrogen allows us to evaluate the balance of oxides and water in this system according to Equations (2) and (3) of Klein et al. (2010).

Looking at the oxide balance in an early-phase interpretation for HS2253, we find that the number ratio of oxygen that can be accounted for by oxides as in the preceding paragraph (using half the iron in FeO, half in Fe$_2$O$_3$, plus aluminum at an Earth-like ratio of Al/Mg = 0.086) is O/Mg = 3.8 ± 0.6. Since the observed amount of oxygen is O/Mg = 5.4 ± 1.1, at the limits of the uncertainties the oxygen can be carried in rocky minerals if iron is predominantly in oxide form; water is not needed to balance the oxides. Generally though, due to the ambiguity of the state of iron and since iron is a major element, there is a sensitive trade-off between metallic iron and water in balancing the oxides. In HS2253 the early-phase abundances can be attributed solely to mineral oxides, but could involve up to $\sim$15% water by mass (limited by the observed hydrogen abundance).

In the steady state for HS2253, the number ratio of oxygen expected to be associated with the observed major elements, Mg, Al, Si, Ca, and Fe, as minerals (half the iron in FeO, half in Fe$_2$O$_3$, plus an Earth-like ratio for Al) is O/Mg = 4.7 ± 0.8, and the ratio of observed oxygen coming from the parent body is O/Mg = 4.5 ± 0.9. In the steady state the ratios agree very well with a rocky mineral oxide composition. Again, since some Fe may have been metallic and there is a range of uncertainty overlap in the O/Mg ratios, there is still sufficient oxygen to allow for some water; the amount of possible water in the parent body under a steady-state interpretation is by mass $\lesssim$7%, limited by the observed hydrogen abundance. While HS2253 does not display an infrared excess, it can be seen from Figures 19 and 20 that this heavily polluted WD has atmospheric abundance ratios that are similar to GD40—an analogous WD that does display an infrared excess.

Could the system be in a dissipating phase? Not likely, since the oxides and water are well balanced in both the early-phase and steady-state interpretations; a dissipative interpretation will eventually run into difficulty with oxides. From the lower panel of Figure 18 in an early-phase interpretation, the abundances of Ti, Mn, Cr, Fe, and Ni are in excellent agreement with bulk Earth values (the Ca overabundance and Si underabundance are similar to GD40). As accretion–diffusion proceeds, the ratios move up to the steady-state values. When differential settling dominates, the inferred abundance ratios would be driven even further up compared to Mg and Si, while O/Mg decreases, and would imply a parent body that is somehow depleted of the major elements Mg, Si, and O, compared to high abundance ratios of Ca, Ti, Mn, Cr, Fe, and Ni. We have no physical explanation for how that may occur. Thus, we prefer the simpler explanation that HS2253 most likely accreted material with abundances predominantly similar to bulk Earth and is somewhere at or between an early phase and a steady state of accretion and diffusion.

6.2. PG1225-079 Composition

In addition to significant high-Z element pollution, PG1225 has a considerable amount of hydrogen in its convective zone. Where did it come from? For GD362, Jura et al. (2009) showed that the presence of circumstellar dust, high-Z material, and copious hydrogen can simultaneously be explained by the accretion of a large ice-rich planet. Figure 1 of Jura et al. (2009) illustrates that the atmospheric pollution by hydrogen in GD362 and GD16 is anomalously high compared to other known helium-dominated externally polluted WDs of their evolutionary epoch, 10,500 K < $T_{\text{eff}}$ < 11,500 K, i.e., cooling age 0.4–1 Gyr. At a similar cooling age, our set of possible models for PG1225 indicates a hydrogen mass which can range from $6 \times 10^{22}$ to $8 \times 10^{23}$ g. Referring to Figure 1 of Jura et al. (2009) this is similar, perhaps on the high end, but not extraordinary, compared to the average amount of accreted hydrogen in the set of helium-dominated WDs with detected hydrogen at this age. Jura & Xu (2010) suggest that the origin of the hydrogen in these more ordinary WDs may be from the accretion of ice-rich planet(esimal)s which survive post-main-sequence evolution.

Unfortunately, we cannot evaluate a water and oxide balance for PG1225 since the O $\lambda$7775 lines are not visible in its HIRES spectrum. If the detected elements came from a rocky parent body, then the amount of oxygen (by number) associated with mineral oxides is O/Mg $\sim$5, which is far below the sensitivity of our observations that yield an upper limit of O/Mg < 60 (Table 6). With just a small portion of the allowed O/Mg number ratio allocated to rocky oxides, the remaining number ratio that could be associated with water is O/Mg < 55, but that only accounts for less than 10% of the observed hydrogen. In order to explain all of the observed hydrogen as being derived from icy parent bodies, either an ongoing steady state of atmospheric settling from a somewhat large parent body (perhaps a Ceres analog) or previous ice-rich accretion event(s) would be implied.

PG1225’s spectrum is very rich with high-Z lines and the numerous newly detected elements display an interesting abundance pattern. In the top panel of Figure 18, Mg, Cr, Mn, Fe, and Ni have abundance ratios similar to bulk Earth values, but we find that the refractory elements—Ca, Sc, Ti, and V—are all a factor of $\sim$2–3 higher abundance than in the Earth. High Ca and Ti abundance ratios have previously been measured in GD362 (Zuckerman et al. 2007) and GD40 (Klein et al. 2010). As shown in the bottom panel of Figure 18, HS2253 also has a somewhat enhanced Ca/Mg ratio. The enhancement of refractory element abundances with condensation temperatures >1400 K is significant and uniform in PG1225, and the upper limits derived for Al and Sr are consistent with the trend. One possible explanation for this observation is that the material accreted onto PG1225-079 derived from a planetary body that formed in a higher temperature environment than did the Earth. The simulations of Bond et al. (2010) suggest that refractory-rich exoplanets should be a common outcome of planet formation in nebular regions sufficiently close to the host star.

4 See also Tremblay et al. (2011) for two more recently uncovered candidates of this unusual type of WD—helium dominated with large quantities of atmospheric hydrogen.
PG1225 has just a subtle infrared excess appearing only at 7.9 μm (Farihi et al. 2010b; Kilic et al. 2008a). Farihi et al. (2010b) raise the possibility that it could be due to a relatively narrow dust ring with an inner hole cleared by accretion, suggesting that the system is in a dissipative phase. Referring to Figure 18, since all the refractory elements have shorter settling times than Mg, any “correction” for settling causes an even greater overabundance of refractory species inferred in the parent body. In other words, contrary to the expectation from a dissipative phase, the heavy elements do not appear sunk. However, the settling times in this WD are quite long, ~Myr, and disk lifetimes may be shorter; a large range has been suggested: ~10^8–10^9 yr (Jura et al. 2009, and references therein). Thus, it is conceivable that we could be viewing the system at a point toward the end of an accretion episode but before dissipative differential settling has a significant effect on the atmospheric ratios. Whatever the case regarding circumstellar dust, the atmospheric element ratios imply that PG1225 most likely accreted material with abundances predominantly similar to bulk Earth, but enhanced in refractory species, and the system is somewhere in or near an early phase or steady state of accretion and diffusion.

6.3. Helium-rich Highly Polluted White Dwarfs

Finally, we discuss the set of highly polluted helium-dominated WDs that have been comprehensively studied. To date, five helium-dominated WDs have ≥8 elements reported (GD362, GD40, G241-6, HS2253+8023, PG1225–079) plus two more (SDSS0738, GD61) have measurements of all major (O, Mg, Si, and Fe) terrestrial planetary constituents.

Though our focus in this paper is on compositions in heavily polluted, helium-dominated WDs, we recognize the importance of the study of heavily polluted, hydrogen-dominated WDs, such as NLTT43806 (Zuckerman et al. 2011) and GALEX J193156.8 + 011745 (Vennes et al. 2010). With the detection of circumstellar dust (Debes et al. 2011; Melis et al. 2011) and all the major element species (O, Mg, Si, and Fe), GALEX J193156.8 + 011745 (GALEX1931) is almost certainly accreting a planetary body; with settling times on the order of weeks, accretion must be happening now. However, we note that there is currently a troubling inconsistency between the modeled results of different groups (Vennes et al. 2011; Melis et al. 2011), which is due in part to a large, unexplained difference for the assumed effective temperature (ΔT_eff > 2000 K) of GALEX1931 and in part due to the treatment of atmospheric settling, which for warm (T_eff ~ 20,000 K) hydrogen-dominated WDs is complicated by the lack of a convective envelope.

Figures 19 and 20 represent the compositions by mass of major elements in the helium-dominated polluted WDs in which oxygen has been detected, or a meaningful upper limit set (GD362). Lacking an oxygen detection, PG1225 is not on the bar graphs. There are two different bar graphs showing two different interpretations of the parent body abundances, in the early phase and in the steady state. The graphs are related by ratios of settling times as described in Section 5. We are interested in comparing the bulk accreted compositions, and since hydrogen never settles out of the convective zone, we cannot be certain how much of it is associated with the current heavy element pollution. We do not include hydrogen in Figures 19 and 20, which has a negligible effect on the graph appearance for bulk Earth, HS2253, GD40, SDSS0738, and G241-6, being less than 1% of the accreted mass in those sources. On the other hand, in GD362 hydrogen is over 99% of the accreted mass and in GD61 it is over 75%. As discussed in the preceding section, scenarios have been proposed to explain the presence of hydrogen from the accretion of ice-rich planetary bodies. Now we consider the compositional possibilities from the perspective of oxygen.

In each of the WD systems with detected oxygen, there is always enough O to account for the delivery of the major elements Mg, Si, Ca, and Fe, in the form of a terrestrial-type planetary body. The upper limit of oxygen in GD362 is just enough to have come from Mg, Si, Ca, and Fe in oxides, with the possibility of metallic iron. Since there is very little “spare” oxygen in GD362, in order to account for the hydrogen, high-Z elements, infrared excess, and lack of X-ray luminosity in a unified picture, Jura et al. (2009) calculate a scenario in which settling and accretion have been ongoing for a long time, implying the consumption of a large ice-rich planetary body at least the size of Callisto.

On the right side of the bar graphs, the abundance ratios of GD61 imply the accretion of more oxygen than can be carried in rock. An O “excess” can be the result of dissipative gravitational settling, which would make the abundances seem oxygen-rich and iron-poor. Another way to get an O excess is by the accretion of an ice-rich parent body, as considered in detail by Jura & Xu (2010). The especially high O/Fe and Mg/Fe abundance ratios in the atmosphere of GD61 look suspiciously similar to what is expected in a system where accretion has stopped or paused—the heavier elements sink faster than the lighter ones. However, along with measurements of all the major element abundances, Farihi et al. (2011) report an infrared excess for GD61. Since the WD has plenty of hydrogen in its atmosphere, an O excess, and detected circumstellar material, Farihi et al. (2011) raise again the possibility of the accretion of an ice-rich planetary body. Due to abundance measurement uncertainties and the uncertainty of the accretion–diffusion phase, the results are as yet inconclusive regarding the composition of the parent body accreted onto GD61.

G241-6 also appears to be a case with an O excess, even at the limits of the abundance uncertainties. The upper limit on hydrogen in the atmosphere amounts to less than 1.1% of the mass of detected contaminants, and therefore cannot sufficiently account for the excess oxygen by an origin in ice; the parent body must have been relatively dry. The abundance pattern of G241-6 is similar to GD40 but with Mg, Si, Ca, and Fe appearing “sunk” (compare the GD40 early-phase bar of Figure 19 with G241-6’s steady-state bar of Figure 20). In other words, starting from GD40 abundances, if we could turn accretion off, then eventually gravitational settling will evolve the abundances into ratios similar to what we observe for G241-6. Since we now know from Spitzer data that G241-6 does not have an infrared excess (Xu & Jura 2011), it is likely that G241-6 is in a dissipative phase, having originally accreted an ice-free planetary body with composition similar to GD40 and the bulk Earth.

The abundances in the remaining three, HS2253, GD40, SDSS0738, are all consistent with the major elements being derived from rocky mineral oxides, and a composition similar to bulk Earth being composed more than 85% by mass in O, Mg, Si, and Fe, for either a steady-state and/or early-phase interpretation. Overall their parent body compositions are depleted of volatiles; in addition to the dearth of carbon in GD40 and HS2253, all of them have distinctively low abundances.

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5 Aluminum may also be expected in comparable mass as Ca, but it is more difficult to detect. Within uncertainties, the undetected presence of Al at an Earth-like abundance will not substantially change the oxide balance.
of hydrogen (compared to high-Z elements) and little, if any, excess oxygen—again indicating a dearth of ice in the accreted material.

While GD362 and GD61 are candidates for exoplanetary systems having accreted a substantial amount of water, the other four stars with oxygen measurements must have accreted relatively dry planetary bodies (≤10% H₂O by mass). Furthermore, in all four of those cases, the pollution is most plausibly dominated by planetesimal(s) that formed with little or no ice, for reasons as follows. GD40 and SDSS0738 both have an infrared excess and, as discussed by Jura (2008), the existence of a dust disk is best understood as resulting from the disruption of a single parent body, rather than multiple parent bodies—which, arriving on trajectories of varied inclinations, tend to result in gaseous disks due to dust grain destruction by sputtering in high-velocity impacts. With a minimum accreted mass of ~10^{-22} g, and a rock density of 3 g cm^{-3}, the radius of a single polluting parent body is greater than ~100 km. Thermal erosion calculations by Jura & Xu (2010) demonstrate that asteroids of radii >100 km would have retained at least 50% of their internal ice, if present, through red giant evolution. Thus, the parent bodies polluting GD40 and SDSS0738 most likely formed without much ice.

Could HS2253 and G241-6 be polluted by many small (radius <20–30 km), initially ice-rich asteroids whose internal water was lost during the host star’s asymptotic giant branch (AGB) phase? Consider a model for HS2253 involving 25 km asteroids that were 25% water by mass before the star was on the AGB. According to Figure 4 of Jura & Xu (2010), unless they originally orbited at less than 5 AU, 25 km asteroids would retain at least 10% of their water during AGB evolution of a 3 M⊙ star. At a density of 2.1 g cm^{-3} (analogous to Ceres), the pre-AGB asteroid might have had 10^{-20} g of high-Z material and 4 × 10^{18} g of hydrogen (H) from ice. After the AGB, the asteroid has 10^{-20} g of high-Z material and 4 × 10^{17} g of H. With the middle model from Table 4, the convective zone of HS2253 has ~2 × 10^{22} g of high-Z material. Therefore, it needs to have accreted about 200 asteroids during the most recent 10^{7} years, or about 1 asteroid every 500 years. During this time, the WD would acquire 8 × 10^{19} g of H, about a quarter of the total H (~3 × 10^{20} g with the middle model from Table 4), which the WD has accumulated over its entire cooling age of approximately 400 Myr. The relatively small amount of H in the convective zone implies that no more than ~600 similar asteroids could have arrived in the previous 400 Myr. Why would the asteroids arrive at a rate of 0.002 yr^{-1} recently and 2 × 10^{-6} yr^{-1} previously? The result of this model exercise is analogous, but more extreme, for G241-6. Another difficulty with the above hypothesis is that, even if there is a burst of impacts, one imagines that there would be a size distribution of impactors and, at least in the usual kind of model, most of the mass would be carried in the larger objects. All that is required to produce the observed hydrogen is the accretion of a single ice-rich asteroid of radius 100 km. Unless the size distribution of asteroids is very steep, there could easily be one big asteroid for every 200 small ones. Therefore, to explain the pollutions of HS2253 and G241-6 by swarms of initially ice-rich small asteroids would require both a spike in time of number frequency and a spike in the size distribution of the asteroids. This double constraint seems implausible. It is most likely that the planetesimal(s) which pollute these four now comprehensively studied WDs—HS2253, GD40, SDSS0738, and G241-6—were formed with little ice, and we are measuring the distilled elemental compositions of bodies which condensed out of protoplanetary disks at radii interior to any snow line.

7. CONCLUSIONS

We have obtained and analyzed high-resolution optical spectra of HS2253+8023 and PG1225-079 with HIRES at Keck Observatory. This work adds two more systems to the small but fast-growing sample of polluted WDs with detailed and comprehensive analyses. Four out of six objects with oxygen measurements most likely accreted planetesimal(s) of mineral oxide constitution, which were nearly ice-free, consistent with formation interior to a snow line. It is clear that extrasolar planetary systems produce rocky bodies that are compositionally similar to terrestrial planets in our own solar system; Earth-like planetesimal(s) apparently do form elsewhere in the galaxy.

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