

ABUNDANCE OF ELEMENTS BEYOND THE IRON GROUP IN COOL DO WHITE DWARFS

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ABSTRACT

We report the presence of elements beyond the iron group in the atmospheres of the cool DO white dwarfs HD 149499 B and HZ 21. Photospheric lines of germanium ($Z = 32$), arsenic (33), selenium (34), tin (50), tellurium (52), iodine (53), and perhaps bromine (35) are observed in ultraviolet spectra of HD 149499 B obtained with the *Far Ultraviolet Spectroscopic Explorer (FUSE)*, the Goddard High Resolution Spectrograph (GHRS), and the *International Ultraviolet Explorer*. Germanium, arsenic, and tellurium are also observed in *FUSE* and GHRS spectra of HZ 21. Light elements such as carbon, silicon, phosphorus, and sulfur are present in the atmospheres of both stars. Nitrogen is detected in HZ 21 but not in HD 149499 B. We calculated a grid of synthetic spectra covering the range of effective temperatures, surface gravities, and element abundances appropriate for a detailed line profile analysis. The measured mass fractions of elements heavier than iron reveal overabundances ranging from about a factor of 3 to a factor of 1000 relative to the Sun. The heavy-element enrichment in both stars could be the result of slow neutron capture nucleosynthesis, which would have occurred during the asymptotic giant branch phase of their evolution.

Subject headings: stars: abundances — stars: individual (HD 149499 B, HZ 21) — white dwarfs

1. INTRODUCTION

DO white dwarf stars have helium-rich atmospheres with effective temperatures ranging from $T_{\text{eff}} \approx 120,000$ to $\approx 45,000$ K. The temperatures of cool DO white dwarfs mark the hot end of the so-called DB gap, which corresponds to an interval in effective temperatures ($45,000 \text{ K} \geq T_{\text{eff}} \geq 30,000 \text{ K}$) devoid of helium-rich white dwarfs (Liebert et al. 1986). DO white dwarfs may be the descendants of the PG 1159 stars, a class of objects that have lost their hydrogen envelope and acquired a He/C/O-rich surface due to processes involving a late helium shell instability during the pre-white dwarf phase (Herwig et al. 1999). As DO white dwarfs cool down, their strong gravitational field favors the downward diffusion of elements heavier than helium. However, the detection of trace elements in the atmospheres of DO white dwarfs implies that some mechanisms, such as convection, turbulence, accretion, or radiative levitation, interfere with gravitational settling (see, e.g., Fontaine & Michaud 1979; Vauclair et al. 1979; Vennes et al. 1988; Dupuis et al. 1993; Chayer et al. 1995; Dreizler 1999). The observation of elements beyond the iron group in the atmospheres of these high-gravity stars may contribute to our understanding of the chemical evolution of white dwarfs, not only with the identification of the mechanisms responsible for the observed abundances, but also by assessing the nucleosynthesis of heavy elements in asymptotic giant branch (AGB) stars.

In this paper, we report the observation of elements beyond the iron group, collectively referred to as heavy elements, in the atmospheres of the cool DO white dwarfs HD 149499 B ($T_{\text{eff}} = 49,500$ K; Napiwotzki et al. 1995) and HZ 21 ($T_{\text{eff}} = 53,000$ K; Dreizler & Werner 1996). In § 2, we discuss the observation of germanium, arsenic, selenium, tin, tellurium, iodine, and perhaps bromine in *Far Ultraviolet Spectroscopic Explorer (FUSE)*, Goddard High Resolution Spectrograph (GHRS), and *International Ultraviolet Explorer (IUE)* spectra of HD 149499 B, as well as the observation of germanium,

arsenic, and tellurium in *FUSE* and GHRS spectra of HZ 21. Incidentally, germanium has also been observed in the atmospheres of the hot DA white dwarfs G191-B2B, Feige 24, and GD 246, and tin has been detected in the atmosphere of G191-B2B (Vennes et al. 2005). We carry out a spectroscopic analysis in § 3, and we show in § 4 that the high heavy-element abundance in HD 149499 B and HZ 21 may imply that nucleosynthesis by slow neutron capture (*s*-process) took place during the AGB phase of their evolution.

2. OBSERVATIONS

HD 149499 B and HZ 21 were observed by *FUSE*, which covers the wavelength range from $\lambda \approx 905$ to 1187 \AA with a resolution $R \approx 17,000$. HD 149499 B was observed repeatedly in the course of the *FUSE* mission as part of the M103 calibration program to monitor the stability of the spectrograph flux sensitivity. In the present study, we have combined data obtained using the large square aperture (LWRS: $30'' \times 30''$) from 10 individual observations (M1031101, M1031102, M1031103, M1031105, M1031111, M1031114, M1031117, M1031120, M1031401, and M1031404) leading to a total exposure time of 62,500 s. For HZ 21 we use the P2040801 and M1080201 observations obtained using the LWRS for an exposure time of 17,375 s. In both cases, we have co-aligned the spectra from individual exposures/observations by cross-correlating the spectra in pixel space over small regions that include narrow absorption lines. The spectra were then combined by taking an exposure-weighted average of all observations. In view of its relatively intense far-UV flux (flux at 1050 \AA of $2.4 \times 10^{-11} \text{ ergs s}^{-1} \text{ cm}^{-2} \text{ \AA}^{-1}$), the combined spectrum of HD 149499 B is of exceptionally good quality with a signal-to-noise ratio exceeding 100 pixel^{-1} in the LiF1A channel at 1050 \AA .

Both stars were also observed with GHRS using the G160M grating ($R = 20,000$) and by *IUE* using the short-wavelength prime (SWP) camera in the high-dispersion mode ($R = 10,000$). Two GHRS spectral bands covering the range from $\lambda \approx 1227$ to 1264 \AA and from 1338 to 1375 \AA were obtained for both stars, and an additional spectral band covering the range from 1699 to 1735 \AA was obtained for HD 149499 B. In the case of the *IUE* data, five spectra were obtained for HD

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149499 B with a total exposure time of 19,320 s, and only one spectrum with an impressive exposure time of 68,820 s was obtained for HZ 21. HZ 21 being much fainter, the signal-to-noise ratio of this long exposure remains much lower than that for HD 149499 B. The same *IUE* data were used by Holberg et al. (1998) in their analysis of high-dispersion SWP spectra of white dwarfs. We retrieved the *IUE* data from the World Wide Web.⁴

Table 1 lists relevant atomic data for all photospheric metal lines identified in the *FUSE*, *GHRs*, and *IUE* spectra of HD 149449 B. The spectra show a wealth of photospheric lines produced by transitions emerging from the ground state or from excited energy levels and from different ionization states. The richness of its spectrum and the variety of trace elements found in its atmosphere make HD 149499 B one of the most interesting hot white dwarfs ever studied. The detection of a single Br VI resonance line at 939.576 Å is tentative. Given that there are many unidentified lines in the HD 149499 B spectrum, the 939.576 Å line could be a transition originating from another, yet unidentified element. Nevertheless, we believe that bromine ($Z = 35$) should be present in the atmosphere of HD 149499 B because of the similarity of its atomic and nuclear properties with germanium (32), arsenic (33), and selenium (34).

Resonance lines of Ge IV at 1229.840 Å, As V at 987.651 and 1029.48 Å, and Te VI at 951.02 and 1071.40 Å are observed in the atmosphere of HZ 21. Light elements such as carbon, silicon, phosphorus and sulfur are detected in the spectra of both stars. Strong nitrogen lines are observed in HZ 21, but none is detected in HD 149499 B. Although a large number of lines have been identified in the *FUSE* spectrum of HD 149499 B, there are many more weak and strong lines that remain unidentified. The identification of weak lines in the *FUSE* spectrum of HZ 21 is more difficult because of its lower signal-to-noise ratio. Nevertheless, two strong, unidentified lines at 952.83 Å (EW = 32.0 mÅ) and 1157.85 Å (18.1 mÅ) stand out in the *FUSE* spectrum. We believe that the line at 952.83 Å is also present in the spectrum of HD 149499 B. On the other hand, the line at 1157.85 Å in HZ 21 does not match the line at 1157.53 Å in HD 149499 B. Finally, there are many interstellar absorption lines detected in the *FUSE* spectra of HD 149499 B and HZ 21. Absorption lines such as H I, D I, C II, C III, N I, N II, O I, Si II, P II, Ar I, and Fe II are observed along the lines of sight to HD 149499 B and HZ 21. Wood et al. (2002) and Oliveira et al. (2003) carried out detailed analyses of these lines of sight.

3. SPECTRAL ANALYSIS

The abundance measurements are obtained following different techniques depending on the availability of atomic data. It turns out that energy levels, oscillator strengths, and photoionization cross sections, which are needed for computing non-LTE (NLTE) stellar atmosphere models, are much better known for the light elements C, N, Si, P, and S than for the heavy elements Ge, As, Se, Br, Sn, Te, and I. As a result, we computed a grid of NLTE models composed of three elements, H, He, and “Z,” where Z is either C, N, Si, P, or S. The models are computed for a set of abundances varying from $\log [N(Z)/N(\text{He})] = -5.2$ to -10.0 , in steps of 0.4 dex. The corresponding synthetic spectra are then computed for this set of models and applied to the abundance analysis one element at a time. In the case of the heavy elements, a grid of synthetic spectra is computed from NLTE models with a H/He chemical

TABLE 1
PHOTOSPHERIC LINES IDENTIFIED IN *FUSE*, *GHRs*, AND *IUE* SPECTRA OF HD 149499 B

Ion	λ_{lab} (Å)	$\log gf$	g_l	E_l (cm ⁻¹)	EW (mÅ)
C III ^a	1175.7	0.37	9.0	52419	129 ± 3
C IV	1548.195 ^b	-0.419	2.0	0.0	90.5 ± 7.6
	1550.772 ^b	-0.720	2.0	0.0	78.6 ± 7.6
Si IV	1122.485	0.220	2.0	71287.539	8.3 ± 0.7
	1128.325 ^c	-0.480	4.0	71748.641	8.0 ± 0.7
	1128.340 ^c	0.470	4.0	71748.641	8.0 ± 0.7
	1393.755	0.030	0.0	2.0	17.3 ± 3.2
	1402.770	-0.280	0.0	2.0	14.6 ± 4.5
P V	1117.977	-0.010	2.0	0.0	16.7 ± 0.8
	1128.008	-0.320	2.0	0.0	11.7 ± 0.7
S VI	933.378	-0.040	2.0	0.0	6.6 ± 1.1
	944.523	-0.350	2.0	0.0	6.8 ± 0.8
Ge IV	1229.840	-0.302	2.0	0.0	16.7 ± 1.8
As IV	946.5	...	1.0	75812	15.1 ± 0.9
	953.3	...	5.0	79492	22.9 ± 0.7
	956.9	...	3.0	76962	10.5 ± 0.8
	971.1	...	3.0	76962	12.3 ± 0.9
	980.6	...	5.0	79492	19.1 ± 0.8
	999.3	...	5.0	79492	14.7 ± 0.9
	1003.4	...	3.0	112022	16.4 ± 1.0
As V	987.651	0.023	2.0	0.0	50.5 ± 1.6
	1029.48	-0.296	2.0	0.0	48.2 ± 1.2
	1051.6	...	4.0	236897	8.8 ± 0.4
	1056.7	...	...	...	9.6 ± 0.6
Se III	938.3	...	1.0	0.0	8.1 ± 1.1
	1000.4	...	...	...	16.4 ± 0.9
Se IV	959.59	-0.813	2.0	0.0	17.4 ± 1.2
	996.71	-0.574	4.0	4376.0	26.6 ± 0.9
	1001.65	-1.530	4.0	4376.0	9.5 ± 0.6
	1018.0	...	...	...	9.5 ± 0.9
	1157.3	...	6.0	104706	9.0 ± 0.7
	1166.8	...	4.0	104211	7.9 ± 0.6
	1176.4	...	6.0	104706	12.1 ± 0.9
	1259.519 ^d	...	2.0	0.0	26.2 ± 1.6
Se V	1094.68	-2.534	1.0	0.0	18.3 ± 1.0
	1151.0	...	3.0	131733	23.6 ± 0.7
	1227.6	...	3.0	131733	25.5 ± 1.7
Br VI	939.576	-2.380	1.0	0.0	10.3 ± 0.9
Sn IV	956.249	...	2.0	69563.9	3.4 ± 0.5
	1019.719	...	4.0	76072.3	8.6 ± 0.8
	1044.487	...	2.0	69563.9	18.8 ± 0.7
	1073.407	...	4.0	76072.3	8.4 ± 0.5
	1314.539	0.105	2.0	0.0	45.9 ± 4.7
Te VI	951.02	0.063	2.0	0.0	13.6 ± 0.7
	1071.40	-0.276	2.0	0.0	24.1 ± 0.6
I V	1003.924	-0.727	4.0	12222.1	44.7 ± 0.9
	1017.715	...	6.0	111831.2	8.1 ± 0.9
	1044.998	...	4.0	108780.4	5.1 ± 1.1
	1067.908	...	4.0	139398.1	6.7 ± 0.5
	1234.516	...	2.0	0.0	21.8 ± 3.4
	1244.831	-1.308	4.0	12222.1	24.9 ± 2.5
I VI	1120.301	...	1.0	0.0	39.0 ± 0.8

NOTE. — Atomic data are from Kelly (1987), Kaufman et al. (1988), Hirata & Horaguchi (1995; atomic spectral line list available at <http://vizier.u-strasbg.fr/Viz-bin/ftp-index?VI/69>), Kurucz & Bell (1995), Tauheed et al. (1998), and Morton (2000).

^a Multiplet.

^b The photospheric lines are blended with circumstellar lines.

^c The lines at 1128.325 and 1128.340 Å are blended, so the equivalent widths listed are the total equivalent width corresponding to this blend.

^d The Se IV line at 1259.519 Å is blended with the interstellar S II line at 1259.518 Å.

composition, treating the heavy elements under the assumption of LTE and the trace-element approximation.

Both models and synthetic spectra are computed using the stellar atmosphere and spectral synthesis codes TLUSTY and SYNSPEC (Hubeny & Lanz 1995). We used the modification that Proffitt et al. (2001) made to the program SYNSPEC to

⁴ Available at <http://vega.lpl.arizona.edu>.

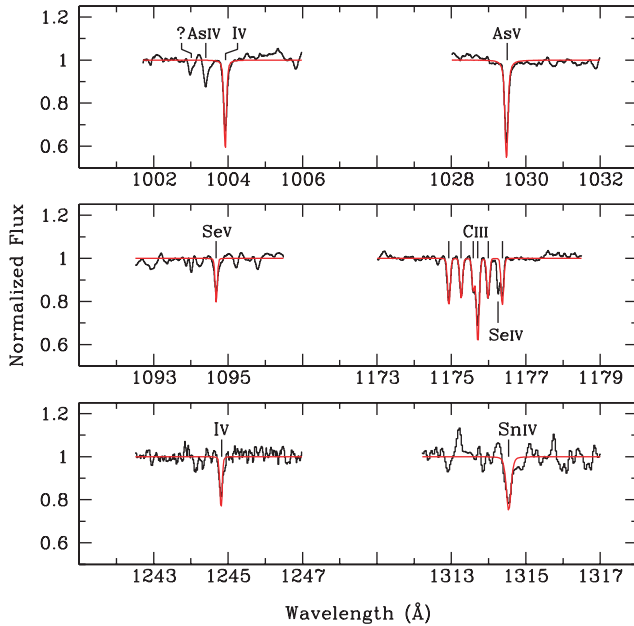


FIG. 1.—Examples of photospheric lines observed in *FUSE*, *GHRS*, and *IUE* spectra of HD 149499 B (black lines) and best models matching the observed spectra (red lines). The top two panels show *FUSE* data. The left and right spectra in the bottom panel show *GHRS* and *IUE* data, respectively. The As iv $\lambda 1003$ and Se iv $\lambda 1176$ lines are not included in the fits of the 1002–1006 and 1173–1179 Å spectral regions, because their oscillator strengths are not known.

include the partition functions for the neutral, +1, and +2 ionization stages of elements heavier than zinc. For the +3, +4, and +5 ions we modified SYNSPEC to compute the partition functions explicitly. For HD 149499 B, we adopted the atmospheric parameters measured by Napiwotzki et al. (1995), $T_{\text{eff}} = 49,500$ K, $\log g = 7.97$, and $\log [N(\text{H})/N(\text{He})] = -0.65$, and for HZ 21 we adopted the parameters measured by Dreizler & Werner (1996), $T_{\text{eff}} = 53,000$ K, $\log g = 7.8$, and $\log [N(\text{H})/N(\text{He})] = -1.0$. Abundances of both light and heavy elements are obtained by fitting each line under consideration (lines with known gf) with a χ^2 minimization technique, where the abundance relative to helium and a normalization factor are treated as free parameters. Figure 1 shows a few examples of our best fits for HD 149499 B, and Table 2 summarizes our spectroscopic analysis for both HD 149499 B and HZ 21.

4. ON THE HEAVY-ELEMENT ENRICHMENT

The detection of elements beyond the iron group in the atmospheres of the cool DO white dwarfs HD 149499 B and HZ 21 raises fundamental questions: Is the heavy-element enrichment a result of nucleosynthesis during the AGB phase, an apparent overabundance created by diffusion processes near the stellar surface, or both?

The most striking result of our spectroscopic analysis is the presence of elements with $Z > 31$ and with abundances larger than solar abundances. Table 2 compares the mass fractions of elements observed in the atmospheres of HD 149499 B and HZ 21 with the solar mass fractions. All light elements (C, N, Si, P, and S) have mass fractions smaller than those in the Sun by 1–4 orders of magnitude. These underabundances are comparable to those observed in DA white dwarfs and come, at least qualitatively, within the scope of the diffusion theory (see,

TABLE 2
METAL ABUNDANCES IN HD 149499 B AND HZ 21

ION	HD 149499 B		HZ 21	
	Number ^a	Mass ^b	Number ^a	Mass ^b
C III $\lambda\lambda 1175$	-6.51 ± 0.01	-3.53	-6.46 ± 0.07	-3.46
N III $\lambda\lambda 980$ .....	...	...	-5.55 ± 0.21	-1.95
N III $\lambda\lambda 991$ .....	...	...	-5.66 ± 0.07	-2.06
N III $\lambda\lambda 1184$ .....	...	...	-5.40 ± 0.11	-1.80
N IV $\lambda\lambda 923$	< -7.47	< -3.88	-5.27 ± 0.12	-1.67
N IV $\lambda 955$ .....	...	...	-5.62 ± 0.14	-2.02
N V $\lambda\lambda 1240$	< -6.53	< -2.94	-5.39 ± 0.04	-1.79
Si IV $\lambda\lambda 1126$	-7.80 ± 0.04	-3.94	-6.30 ± 0.09	-2.42
Si IV $\lambda\lambda 1397$	-7.82 ± 0.10	-3.96	...	...
P V $\lambda\lambda 1123$	-8.60 ± 0.01	-2.59	-7.07 ± 0.08	-1.05
S IV $\lambda\lambda 1070$ .....	...	...	-6.72 ± 0.09	-2.48
S VI $\lambda\lambda 937$	-6.09 ± 0.08	-1.86	-5.62 ± 0.25	-1.38
Ge IV $\lambda 1230$	-7.63	0.17	-7.45 ± 0.09	0.36
As V $\lambda 988$	-6.57 ± 0.02	2.52	-7.75 ± 0.34	1.35
As V $\lambda 1029$	-6.22 ± 0.02	2.87	-7.83 ± 0.15	1.27
Se IV $\lambda 960$	-6.31 ± 0.05	1.73	...	...
Se IV $\lambda 997$	-6.29 ± 0.04	1.75	< -6.16	< 1.89
Se IV $\lambda 1002$	-6.22 ± 0.05	1.82	...	...
Se V $\lambda 1095$	-5.97 ± 0.03	2.07	< -6.68	< 1.37
Br VI $\lambda 940$	-4.35 ± 0.07	4.47	...	...
Sn IV $\lambda 1315$	-6.58 ± 0.10	2.80	...	...
Sb V $\lambda 1104$	< -9.84	< 0.53	< -9.17	< 1.21
Te VI $\lambda 951$	-7.70 ± 0.05	1.48	-7.35 ± 0.27	1.84
Te VI $\lambda 1071$	-7.45 ± 0.02	1.73	-7.42 ± 0.07	1.77
I V $\lambda 1004$	-6.14 ± 0.03	3.74	< -7.43	< 2.45
I V $\lambda 1245$	-6.36 ± 0.08	3.52	...	...
Pb IV $\lambda 1029$	< -7.93	< 1.44	< -6.49	< 2.89

^a Values given are $\log [N(\text{Z})/N(\text{He})]$.

^b Mass fraction relative to the solar value: $\log X_{\text{Z}} - \log X_{\text{Z}}^{\odot}$. The solar abundances are from Asplund et al. (2005). Abundances of As, Se, Br, Te, and I are from meteoritic abundances.

e.g., Barstow et al. 2003; Vennes & Lanz 2001). On the other hand, the overabundance of elements such as As, Se, Br, Sn, Te, and I observed in the atmosphere of HD 149499 B challenges our understanding of the spectral evolution of white dwarfs.

Vauclair et al. (1979), Chayer et al. (1995), and Dreizler (1999) show that selective radiation pressure on heavy elements can offset the effect of gravitational settling and support trace elements in hot white dwarf atmospheres ($T_{\text{eff}} \geq 20,000$ K). Moreover, this parameter-free diffusion model stipulates that stars with similar atmospheric parameters must have similar heavy-element abundances. HD 149499 B and HZ 21 have similar atmospheric parameters with T_{eff} and $\log g$ differing by less than a few thousand degrees and by less than 0.2 dex, respectively. Both stars should, in principle, exhibit comparable abundances or at least comparable abundance patterns. However, Table 2 shows very puzzling abundance patterns if we attempt to explain them within the framework of the radiative levitation theory. Both stars have identical C abundances, and although HZ 21 has a relatively high N abundance, HD 149499 B does not show any trace of nitrogen. Si and P are more abundant in the atmosphere of HZ 21 by factors of about 30 and 40. Based on the higher abundances of N, Si, and P observed in HZ 21, we would expect that elements beyond the iron group would be more abundant in HZ 21 than in HD 149499 B. On the contrary, the abundance of heavy elements with $Z > 33$ is much lower in HZ 21 than in HD 149499 B. This dichotomy between light- and heavy-element abundances is very difficult to interpret with a parameter-free diffusion model. Chayer et al. (1995) suggested that weak stellar winds could compete with gravitational settling and radiative levitation and build abundance anomalies in white dwarf atmo-

spheres. It may be that a weak wind is present in one of the stars and is responsible for differences in the abundance patterns; however, detailed diffusion calculations exploring this possibility are not currently available.

Could nucleosynthesis during the AGB phase (see Busso et al. 1999 for a review of nucleosynthesis in AGB stars) generate an abundant supply of heavy elements such as elements from the Zr peak (light *s*-process elements, ls), the Ba peak (heavy *s*-process elements, hs), and Pb at the termination of the *s* path? Heavy elements are synthesized in the intershell region via neutron capture seeded mainly by the $^{13}\text{C}(\alpha, n)^{16}\text{O}$ reaction, with an additional role played by the $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ reaction. The ^{13}C is assumed to reside in a pocket below the convective envelope in the intershell region, where protons somehow diffused into and were captured by ^{12}C atoms. The newly synthesized heavy elements are subsequently mixed in the envelope during the following convective thermal pulse, resulting in a gradual envelope enrichment. Evidence for such *s*-process enrichment processes has been found in PG 1159 stars by Werner et al. (2004, 2005). It is recognized that along with stellar mass variations, metallicity variations may account for different families of chemically peculiar stars. Although attractive, the proposition that heavy elements in the cool DO white dwarfs HD 149499 B and HZ 21 were synthesized while on the AGB

lacks critical supporting measurements. The iron abundance, which is affected by *s*-process nucleosynthesis, is required in both objects, as well as key hs and ls abundances, although we found evidence that Pb is lacking. Perhaps some unidentified lines in HD 149499 B belong to the hs or ls groups. Still, based on current evidence, we propose that both stars show the effect of nucleosynthesis during the AGB phase of their evolution and that different progenitor properties led to the noted spectroscopic differences between HD 149499 B and HZ 21. Following the “born-again” scenario (Iben & MacDonald 1995; Herwig et al. 1999), the PG 1159 stars, and their likely DO white dwarf descendants, expose helium envelopes enriched with *s*-process elements. The heavy-element abundance pattern in HD 149499 B and HZ 21 is quite distinct from DA white dwarf abundance patterns (Vennes et al. 2005), which do not exhibit the dramatic heavy-element enrichment found in cool DO white dwarfs.

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