HUBBLE SPACE TELESCOPE OBSERVATIONS OF COOL WHITE DWARF STARS: DETECTION OF NEW SPECIES OF HEAVY ELEMENTS[1]

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ABSTRACT

Observations of cool white dwarf stars with the *Hubble Space Telescope* has uncovered a number of spectral features from previously unobserved species. In this paper we present the data on four cool white dwarfs. We present line identifications, equivalent width measurements, and brief summaries of the significance of our findings. The four stars observed are GD 40 (DBZ3), G 74-7 (DAZ), L 745-46A (DZ), and LDS 749 B (DBA). Many additional species of heavy elements were detected in GD 40 and G 74–7. In L 745–46A,while the detections are limited to Fe I, Fe II, and Mg II, the quality of the Mg II h and k line profiles should permit a test of the line broadening theories, which are so crucial to abundance determinations. The clear detection of Mg II h and k in LDS 749 B should, once an abundance determination is made, provide a clear test of the hypothesis that the DBA stars are the result of accretion from the interstellar medium. This star contains no other clear features other than a tantalizing hint of C II 1335 with a P Cygni profile, and some expected He I lines.

1. INTRODUCTION

White dwarf stars are the final evolutionary states of low-mass stars like the Sun. Consequently, their study can illuminate many aspects of the late evolution of low-mass stars and the role of mass loss during the red giant stage. More specifically, a number of us have hoped that the chemical composition of white dwarf surfaces would provide some hints as to what happened during the red giant stage of the stars we now see as white dwarfs. A major peculiarity of white dwarf stars is their division between a group of stars which are predominantly hydrogen photospheres (the DA stars) and a group that is predominantly helium (spectral types DB and DZ). If helium-rich stars are too cool to show helium lines, all they show are heavier elements, thus the classification of DZ is appropriate. Sion *et al.* (1983) defined the spectral classifications of white dwarf stars; some comments on the subsequent evolution of this classification system can be found in Wesemael *et al.* (1993). Another peculiarity is that many white dwarf stars, in particular, the cooler ones, show signs of heavy elements in their spectra. This is somewhat unexpected, since the gravitational fields of white dwarf stars are so strong that he compositions of their photospheres should be monoelemental, as Schatzman (1958) first realized many years ago.

One specific proposal relating the composition of white dwarf stars to previous episodes in their life cycle came from Iben and co-workers about ten years ago (see Iben & MacDonald 1985,1986; MacDonald & Vennes 1992). Specifically, the relative timing of mass loss during the thermally pulsing stages of a red giant on its second trip up the asymptotic giant branch would determine which of the two major types of white dwarf star a star would become. This proposal produced a great deal of discussion, and generated a specific counterproposal on how mixing during the white dwarf stage of a star's life cycle could turn DA white dwarf stars into DBs, and vice versa (Fontaine & Wesemael 1987). A discussion of the competing merits of these two schemes can be found in Shipman (1989).

A most significant complication in this picture is the role of accretion from the interstellar medium. The photospheres of white dwarf stars are very thin, and so accretion can significantly pollute their photospheres, changing their composition. The photospheric compositions of white dwarfs are quite different from the composition of the surrounding interstellar medium, which can itself be fractionated into gas and dust components.

Progress in this line of investigation on the observational side has largely come when advances in ground- and space-based instrumentation have resulted in the discovery of additional species of elements in white dwarf stars. Particular hypotheses of the origin of this or that chemical peculiarity often produce very specific predictions regarding what types of elements should be found in the spectrum of different kinds of white dwarf stars. The advent of the *Hubble Space Telescope (HST)* promised a dramatic change in our capabilities in the ultraviolet part of the spectrum. It has now been nearly ten years since a group of workers who study white dwarf stars coalesced into a massive team, whose purpose was to collaborate on the study of white dwarf stars with *HST*. I have separately given an account of the genesis of this collaboration (Shipman 1991). This paper is the first report on results from the observation of four cool stars with the *HST*.

2. OBSERVATIONAL PROCEDURE

The selection of which stars to observe was the result of some extended discussion, largely conducted by electronic mail during the years when the *HST* program was suffering from the launch hiatus produced by the Challenger explosion. Our decisions about cycle 1 observations were largely driven by the desire to produce some tangible new results to guide future observations of white dwarfs with the *HST*. An additional consideration is that many of the most interesting cool white dwarf stars are among the very coolest, which are the hardest to observe with an instrument like the *HST*.

Consequently, target selection tended to be biased toward stars, which had already shown some sort of chemical peculiarities, either from the ground or from IUE. For example, we did include two stars on the list (GD 40 and G 74–7)

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TABLE 1. Journal of observations.

Star	Instrument	Grating	Resolution (A/diode)	Wavelength Range or central wavelength	Exposure Time (min)
L745-46A	FOS/BL	G160L	6.9	1150-2523	80
		G270H	2.1	2700	20
GD 40	FOS/BL	G130H	1.0	1380	60
		G190H	1.5	1944	10
		G270H	2.1	2700	10
G 74-7	FOS/RD	G160L	6.6	1700-2400	40
	FOS/RD	G270H	2.1	2225-3293	20
LDS 749 B	FOS/BL	G130H	1.0	1380	20
		G190H	1.5	1944	20
		G270H	2.1	2700	20

because of their unique chemical composition, compositions that when properly interpreted should indicate just where they came from. GD 40 was the first DB star to show spectroscopic indications of heavy elements, first Ca in the visible and then Mg and Fe in the ultraviolet (Wickramasinghe *et al.* 1975; Shipman & Greenstein 1983). G 74–7 is the only star with a spectrum dominated by H lines, showing features produced by heavy elements and thus having a spectrum classification of DAZ. Since observation of this star are only in the optical, the only sign of heavy elements is Ca II H+K. It is simply too faint for *IUE*, but was a logical candidate for *HST*.

The two more "normal" stars on our list were L745-46A and LDS 749 B. L745-46A is one of the brighter, cool DZ stars, and like many other helium-dominated stars of similar temperature, it shows signs of heavy elements in its spectrum, both in the visible and with *IUE* (Zeidler *et al.* 1986). LDS 749 B is the brightest of a group of DB stars, and the only optical spectra of it, obtained some time ago, show no extensive peculiarities. Our hope was that the higher resolution and sensitivity of *HST* might show some hitherto unexpected spectroscopic peculiarities of the DB stars.

These stars, while all fitting into the general category of cool white dwarf stars, also span a fairly wide range of temperatures. LDS 749 B and GD 40 are both DB stars, with temperatures exceeding 10,000 K. Specifically, some reasonable estimates for these objects are $T(\text{eff})=18{,}000$ K for LDS 749 B and $T(\text{eff})=15{,}000$ K for GD 40 (Shipman *et al.* 1986). G 74-7 and L 745–46A are considerably cooler, and thus are classified DZ or DAZ. The discovery paper cited $T(\text{eff})=7400$ K for G 74–7 (Lacombe *et al.* 1983), a value not too different from a more recent value of 7000 K (Hammond *et al.* 1993).

In addition to targets, we also had to choose instrument, wavelength region, and integration times. The cool white dwarf stars contain a variety of spectral features at a wide variety of wavelengths, suggesting that the Faint Object Spectrograph (FOS), which can obtain data on 500–1000 A of spectra at one time, was the instrument of choice. While the Goddard High Resolution Spectrograph has an operating mode in which modest spectral resolution over a range of about 300 A can be obtained, this capability was lost early in the *HST* mission, and thus was never a consideration for cool star observations. Because of the high efficiency of GHRS, following the successful repair mission in 1993 December, it might be an optimal choice for some well-focused, follow-up observations in the future. We elected to cover the entire FOS spectral range for each target, since all of these investigations were pioneering, in the sense that they either were the first investigations of these targets in the ultraviolet, or represented a very considerable improvement over IUE. Since acquisition and data readout typically take at least 15 min per target, the total observing time per target of at least 30 min and typically 1 hr were selected. To cover the entire accessible ultraviolet spectral range, we needed to make two or three exposures with different FOS gratings; given the total amount of time allocated to our project, this limited the exposures for each grating, usually to 30 min at most. We desired optimal S/N ratios in excess of 10 and, for all targets presented here, these expectations were realized in at least some part of the spectral region.

Table 1 lists the observations and exposure times obtained for each target. In all cases, the 1.0 arcsec circular aperture was used for target acquisition. Some motions of the target within the aperture, resulting from spacecraft jitter when the solar panels flexed during transitions from daytime to nighttime orbits, degrade the resolution slightly. Our rationale for using this aperture rather than one of the smaller ones was to maximize the amount of flux that we obtained.

Data were obtained from *HST* in the usual way, and were analyzed using STSDAS on a Decstation at the University of Delaware in Newark. Early on in our analysis procedure we discovered a number of flaws in the FOS calibration tables. Cool white dwarfs do not contain absorption lines with straight sides, flat bottoms, and large width of 5–10 A. These artifacts were produced by inaccurate calibrations of particular diodes, which affect several A of the spectrum because of the stepping pattern of the FOS. They were subsequently removed and do not affect any of the spectra presented here.

After close examination of the spectra, we measured equivalent widths of lines that we regarded as being real or possibly real, using standard routines in IDL. The presence or absence of the lines was determined by visual examination of smoothed spectra, based on standard line lists. Astrophysical reasonableness was used as a criterion in line identification. For consistency, all of the equivalent width measurements were made by one of us (SR). While we measured radial velocities, the 1–2 A resolution of the FOS is sufficiently limited that uncertainties in velocity measurements, which will be ~100 km s^1 or greater, render them not very useful for diagnostic purposes. In most cases, the linewidths were measured using SPLOT's integration of the line strength and determination of the centroid; in a few cases, Gaussian fits were used. Detailed, line-by-line information of velocities and measurement techniques is available from HS or SR.

While we present a nominal flux level for these stars, we note that this flux level is not reliable in absolute terms. Because of spherical aberration in the OTA, some fraction of the flux from the star did not fall on the detector.As a result, the overall flux level in our spectra is less than that found in *IUE* spectra or predicted from models. This loss of UV light should be constant with wavelength; consequently, the slope of the spectra plotted in our figures should be reliable. Put differently, someone wishing to use this spectrum to fit a model should apply a multiplicative factor, generally about 2, to convert our nominal flux to a real flux, thus allowing for the amount of UV radiation that did not strike our detector. This loss may not be absolutely constant from one FOS spectrum to the next, even two different spectra of the same star.

3. RESULTS

3.1 GD 40

GD 40 (=WD 0300-013) has been known as one of the most intriguing DB stars for a long time. (WD numbers refer to the catalog of McCook and Sion 1987.) Wickramasinghe *et al.* (1975) demonstrated that this was the only DB star to show Ca II absorption. A possible weak H-alpha line is discussed in Greenstein and Liebert (1990). Shipman and Greenstein (1983) and Shipman (1984) presented some analyses of *IUE* spectra of this star. The results produced some serious contradictions with the predictions of diffusion theory. The relative abundances of Fe, Mg, and Ca, all of which should be found in the same phase in the interstellar medium, were not in solar ratios, as would be expected. If all of these elements are locked up in the interstellar grains, accretion of the solid phase of the ISM onto a white dwarf star should produce solar abundance ratios. In addition, more volatile elements like C and O were not as abundant as the standard accretion theory of Alcock & Illarionov (1980) would predict.

The *HST* spectrum of GD 40 is shown in Fig. 1. Simple visual inspection of the plot reveals a very rich spectrum. Many of the features were just barely too weak to have been detected with *IUE*, particularly at the shortest wavelengths. Most of the *HST* exposure time was devoted to these short wavelengths, considering the limited sensitivity of the FOS there. The three strongest feature visible in Fig. 1(a) are the Si II resonance lines between 1260 and 1265 A, the important O I resonance at 1304 A, and Si II 1526, 1533. The resonance line of C II at 1335 is also visible.

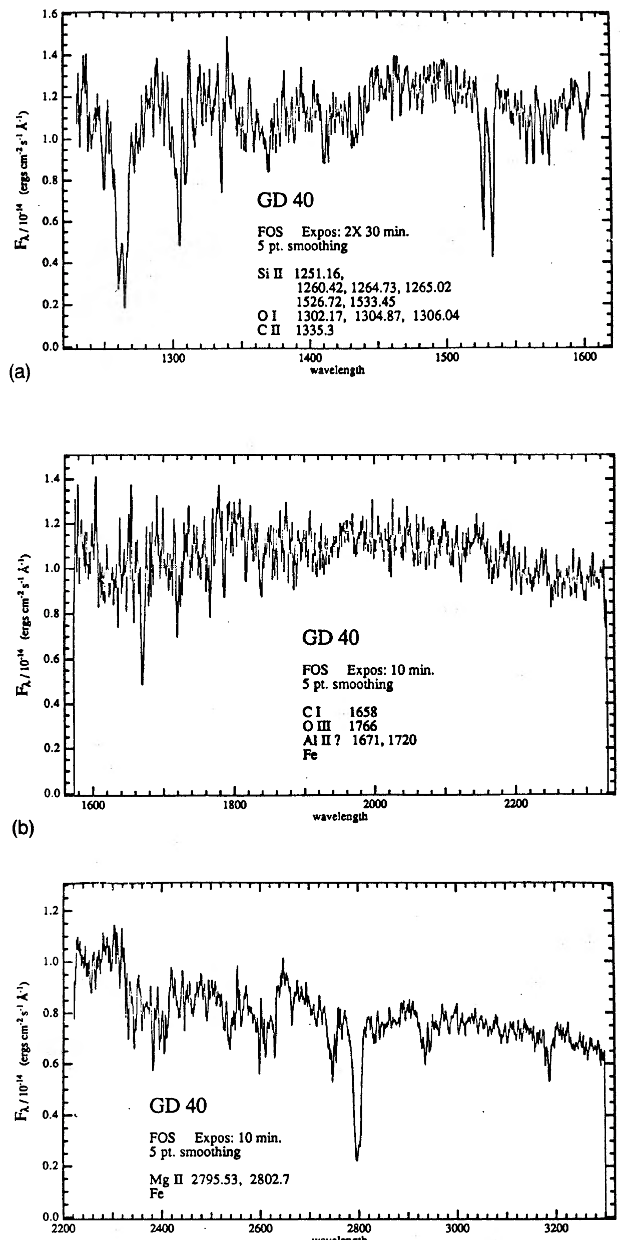


FIG. 1. (a) The far-ultraviolet spectrum of the hot [T(eff)=15,000 K], DBZ star GD 40. (b) The mid-ultraviolet spectrum of the hot [T(eff)=15,000 K], DBZ star GD 40. (c) The near-ultraviolet spectrum of the hot [T(eff) =15,000 K], DBZ star GD 40.

In order to guide the reader as to what features are in the star, and at what strength, we have listed equivalent widths for the lines we see in the spectrum. In some cases, it is likely that abundance analyses could be done using these numbers alone. In cases like the extremely complex Fe II spectrum, abundance analyses would probably have to use the spectra themselves. Table 2 lists identifications, equivalent widths, and line depths for the lines in the spectra that we regard as being real. The line "depth" is measured from the top in units of the continuum; a completely black line will have depth 1.0. Some comments on particular spectrum

TABLE 2. Absorption lines in GD 40.

Feature		Equivalent Width (A)	Depth
Si II	1190.42	p,blend	
Si II	1193.28	p,blend	
Si II	1194.50	3.3	0.85
Si II	1197.42	p,blend	
Si III	1206.52	1.4	0.45
Si II	1227.60	1.9	0.46
Si II	1249.50	2.1	0.45
Si II	1260.42	4.3	0.57
Si II	1264.73	4.9	0.65
O I	1302.17, 1304.87,1306.04	3.0 n	0.65
possibly blended with Si II, III			
Si II	1309.27	1.4	0.44
?	1315.97 (meas)	1.3	0.32
C II	1335.30	1.2	0.48
Si III	1369.44	1.8	0.35
Si II?	1410.22	1.3	0.33
Si II	1526.72	1.6	0.57
Si II	1533.45	2.0	0.67
?	1558.96 (meas)	0.51	0.27
Fe II, Si II	1563.78	0.56	0.28
?	1570.22 (meas)	0.61	0.24
Si I	1574.82	0.65	0.3
?	1671.16	3.8	0.6
Al II	1719.44, 1721.244,	1.5 n	0.27
Al II	1724.98	2.3 n	0.23
O III??	1760.12	1.1 n	0.19
Si I	1763.66, 1765.03, 1766.06	1.9 n	0.29
Fe II	1785.26, 1786.74,5.26	1.8	0.29
Si II	1816.92, 1817.45	1.2	0.19
Si I	1838.01	2.2	0.27
Si I	1887.70	1.3	0.17
?	2122.35 (meas)	1.0	0.18
Si II	2334.40, 2334.61	2.5	0.22
Si II	2344.2, 2350.17	3.4	
Fe II	2327-2380 (UV 3)	n	
Fe II	2382.04	3.4	0.33
Fe II	2395.62	1.9	0.22
Fe II	2404.89	3.3	0.25
Fe II	2330 - 2411 A	n	
Fe II	2538.99	4.5	0.24
Fe II	2538 - 2557 A	n	
Fe II	2562.54	1.2	0.15
Fe II	2599-2632	n	
?	2666.09	1.2	0.15
Fe II	2748.04	4.7 n	0.3
	Above feature is complex of (uv 62,63) lines		
Mg II	2797, 2802	13.4	0.7
Fe II	2926.59	2.1	0.15
Fe II	2907-2979	n	
Fe II	3179.50	0.73	0.12
Fe II	3187.29	2.2	0.23

lines are in order; these lines are identified in the table with an "*n*" notation. The O I resonance line complex near 1302–1306 A overlaps with Si III 1303.32 and Si II 1304.37. We identify this line as O I largely on the basis of astrophysical reasonableness, since this O I line is the strongest one in the ultraviolet spectrum and the presence of C II suggests that the line is O I. It is quite possible that the deblending routine that unsorted the various components of the Al II feature from 1719–1724 A incorrectly allocated the equivalent widths to various components of the blend; abundance analysis for this feature will certainly require detailed line profile fitting. The feature listed as O III in Table 1 is a little blip on the wings of Si I 1764–1766; the resolution of this spectral region is considerably inferior to the spectrum from 1200–1600. It may be real, or it may simply be part of the Si I feature. The complexes of Fe II lines from 2327–2380 A (multiplet UV 3), from 2330–2411 A (multiplets UV2, 35, 36), from 2538–2557 A (multiplets UV 158, 160, 176–178), from 2599–2632 A, from 2562–2631 A (multiplets UV 1, 64, 171–175); and from 2907–2979 A (UV 60) are all too complex to be described by single equivalent width measurements; abundance analyses will require spectrum synthesis techniques. We do present an equivalent width for the many Fe II lines near 2748 A (multiplets UV 62, 63), since it is located enough to be well characterized.

Previous observations of GD 40, from the ground and from IUE, revealed only three elements heavier than helium: Ca, Mg, and Fe. We now have data on Si I and II, C II, Al II, and O I in addition. The line strengths given in Table 2 indicate that some of the stronger lines of C, O, and Si were barely below the threshold of *IUE* detectability. Abundance analyses based on these lines should produce an interesting confrontation between observations of this star and predictions of theories that postulate that these elements come from accretion from the interstellar medium.

3.2 *LDS 749 B*

LDS 749 B (=WD 2129+000) is a DB star, an interesting contrast to GD 40. The visual appearance of the spectrum, presented in Fig. 2, shows remarkably few spectral features; the rich iron complexes in the 2200–2700 A spectral region

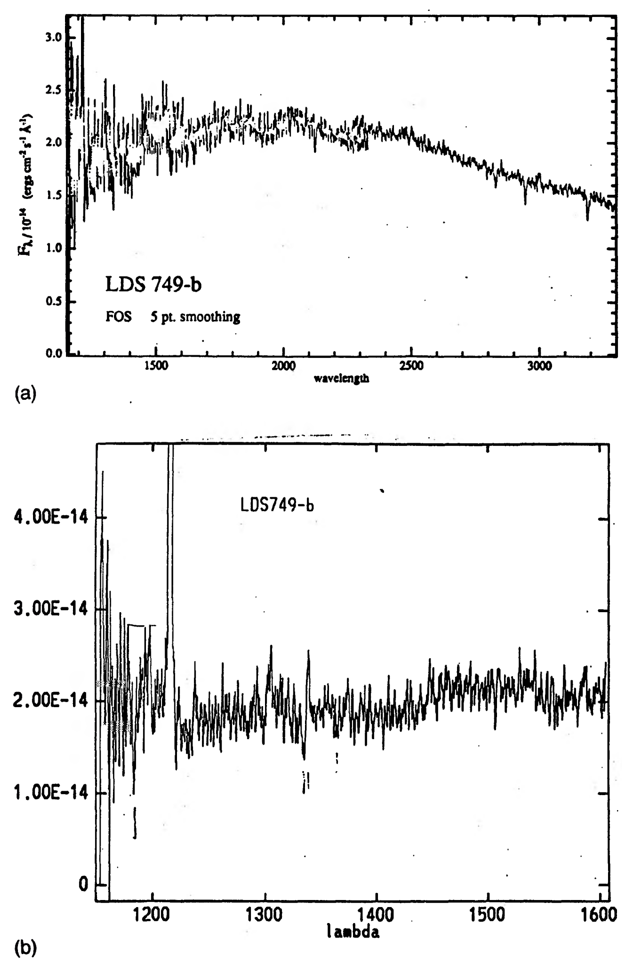
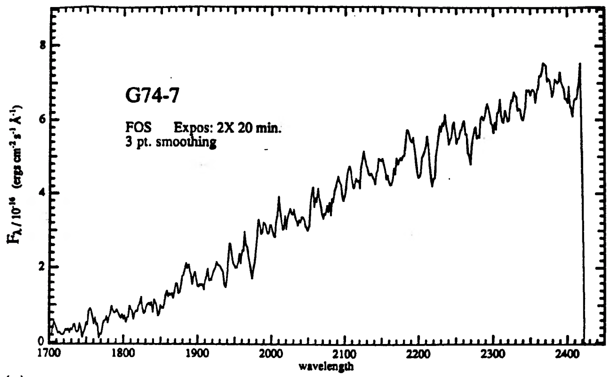


FIG. 2. (a) The near- and mid-ultraviolet spectrum of the hot [T(eff)=18,000 K] DB star LDS 749 B. The step in the spectrum near 2300A is not real, because it is the junction between two separate observations of the spectrum with the FOS. (b) The far-ultraviolet spectrum of the DB star LDS 749 B.



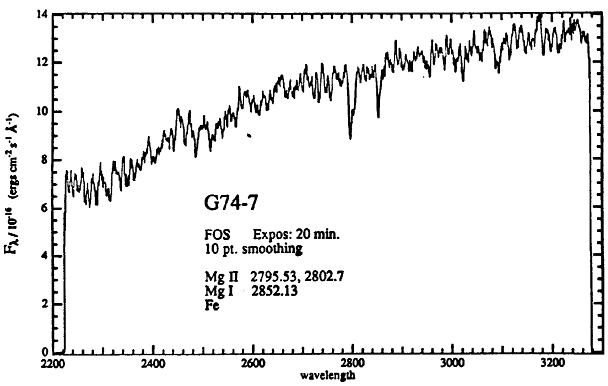


FIG. 3. (a) The mid-ultraviolet spectrum of the cool, DAZ star G 74–7 [T(eff)=7000 K]. (b) The near-ultraviolet spectrum of the cool, DAZ star G 74-7 [T(eff)=7000 K].

are completely absent here. Table 3 lists measurements of the handful of lines in this star, which we regard as being real. A rough, 2-sigma upper limit to the strength of any features in the 1200–1600 A spectral region, based on measurements of dubious features, is 1 A. If this star were to have a spectrum as rich as that of GD 40, it would be quite apparent in our data, even though it is slightly noisier than the data on GD 40. However, an interesting, possible positive identification is a line of Na II 2829. Confirmation of this line as being real awaits an abundance analysis: are there other Na II features in the ultraviolet spectrum, which should be there, and aren't?

3.3 *G 74–7*

The ultraviolet spectrum of this star had never before been measured with any instrument. Since the Ca II feature in ground-based spectra is strong, but not overwhelming, it was surprising (at least to some of us) that the *HST* spectrum turned out to be as rich as it was. Especially at longer wavelengths, there is enough flux in our 20 min exposure (see Fig. 3) to reveal some fairly weak features and even to separate the two components of the Mg II h and k lines.

There is considerable new information about this star that can be gleaned from the absorption lines discovered in this investigation. The lines listed in Table 4 come from Fe I, Fe II, and Mg II. This large assortment of lines should help establish the temperature of this star (through the Fe II/Fe I ionization balance). Abundance determinations should provide an interesting comparison with the much hotter star GD 40; if the relative abundance of Fe, Mg, and Ca remain in nonsolar proportions, as found for GD 40. There is neither enough flux nor enough strength in these line features to permit a test of broadening theories and probe any differences in the broadening of spectral lines by H or by He.

TABLE 3. Absorption lines in LDS 749 B.

Feature		Equivalent Width (A)	Depth
Mg II	2797.99,	0.42	0.09
Na II?	2829.87	1.1	0.12
He I	2945.11	1.2	0.16
He I	3187.74	1.9	0.18

TABLE 4. Absorption lines in G 74–7.

Feature		Equivalent Width (A)	Depth
?	1768.87 (meas)	7.6 n	0.9
Fe I	1937.27	3.1	0.48
?	1972.82	4.9 n	0.46
Fe II	2162.02	3.5 n	0.22
Fe I	2200.72, 2208.41	3.2	0.24
Fe II	2218.26, 2220.4	3.1	0.29
Fe I	2267.47, 2270.86	2.1	0.24
Fe I	2485.99, 2486.69, 2487.07	1.5	0.18
Fe II	2514.38	1.4	0.16
Fe I	2522.85	0.9	0.13
Mg II	2795.53	1.7 n	0.24
Mg II	2802.70	1.4 n	0.16
Mg I	2852.13	1.6	0.2
?	3022.65	0.93	0.14
Fe I	3091.58	1.8	0.12

3.4 *L 745–46 A*

The spectrum of this cool (7800 K), 13th magnitude star had the highest signal/noise in our sample. We obtained more data on this star, since it is quite bright, at least in the near-ultraviolet, and we hoped that obtained high quality data on at least one cool white dwarf might reveal a plethora of weak spectral features. There may be white dwarfs that may show such an abundance of features, but this star is, alas, not one of them.

There are nevertheless a number of interesting features in the ultraviolet spectrum of this star (see Fig. 4). Most prominent among them is an exceedingly well-defined profile of the Mg II h and k lines. These lines had been detected using *IUE* and analyzed for abundances by Koester *et al.* (1982). If the broadening theory is good enough, a detailed comparison of the shape of this line with models may be an extremely sensitive gravity indicator. Since L 745–46 A has a good parallax, precise determination of its surface gravity could add it to the all too short list of stars with independently determined masses and radii.

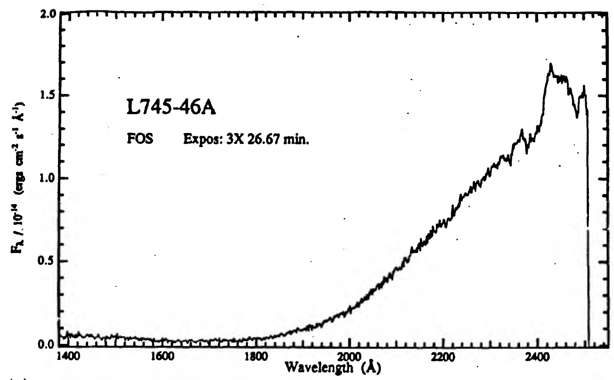
The detections of Fe I and Fe II represent a new species, since Fe had never previously been seen in IUE or in optical spectra. Indeed, we feel sufficiently confident about the high

TABLE 5. Absorption lines in L 745−46 A.

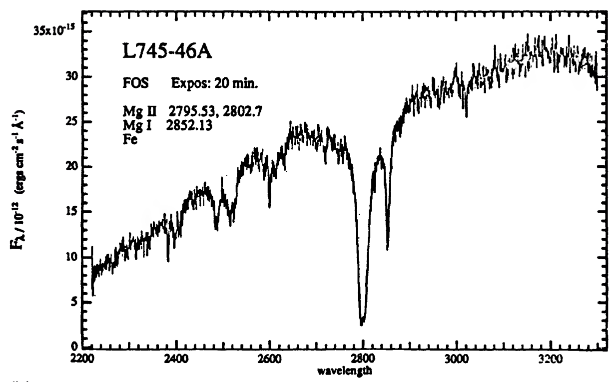
Feature		Equivalent Width (A)	Depth
Fe II	2382.04	1.34	0.29
Fe II	2395.62	2.30	0.26
?	2408.36	1.88	0.13
Fe I	2486.37, 2488.14	4.09	0.17
Si II	2514.35	4.04	0.11
Fe II	2522.85	2.55	0.24
?	2600.05	1.84 n	0.28
Fe II	2631.05	1.14 n	
Fe I+II	2717.83	1.02	0.14
Mg II	2797.99, 2802	50.7	0.9
Fe I	2719.03	0.78	0.13
Mg I	2852.13	4.97	0.49
Fe I	3020.64	0.7	0.13

quality of this spectrum that there is an additional significant figure tabulated in the equivalent width measurements given in Table 4. The data presented here will permit confirmation and refinement of the abundance patterns found here rather than determination of them for the first time. The *HST* spectra show no sign of any C I features in the ultraviolet.

Equivalent widths and line depths are presented in Table 5. We do not pretend that we have completely unsorted the Fe II spectrum in this star. The Fe II 2632 feature, for example, is identified in Table 4, but it appears to be the strongest dip in a fairly complicated set of Fe features, a region that we know to be complex based on its appearance in the spectrum of the much hotter star GD 40. But since this star is cooler, we expect the ionization balance to be considerably different. The two unidentified lines may well be attributable to Fe II, but in the absence of detailed modeling a more precise identification does not make real sense.



(a)



(b)

FIG. 4. (a) The far- and mid-ultraviolet spectrum of the cool DZ star L 745-46 A [$T_{(eff)}$=7800 K). The apparent features in the spectrum near 2400 A do not appear in the spectrum of this star taken with the G270M (?) grating, and are presumably artifacts. (b) The near-ultraviolet spectrum of the cool DZ star L 745-46A [$T_{(eff)}$=7800 K].

4. DISCUSSION AND CONCLUSIONS

The data presented here should permit a significant advance in our understanding of the abundance patterns of cool white dwarf stars. In several stars, most notably the peculiar helium-rich DBZ star GD 40, a number of new chemical species have been uncovered by the higher signal/noise available from *HST*. For L 745−46 A, we have data that is sufficiently good that detailed line profile fitting may permit a precise determination of the Mg abundance and of the surface gravity of an object. An observation that may say more about the difficulties of leaping into a new part of parameter space, where wavelength, resolution, and signal-to-noise are improved greatly over what has been seen before, is that some targets provide a considerable amount of new insight while others simply present refinements of existing data. We have presented data in the form of plots and in the form of tabulated equivalent widths.

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