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An Atlas of Optical Spectra of White-Dwarf Stars[1]

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ABSTRACT. We present a complete atlas of optical spectra of white-dwarf stars. Spectra for all major spectral classes and subclasses are illustrated, and the variation of the dominant spectral features as a function of effective temperature and abundance is documented. We present, as well, spectra of several peculiar or rare types of degenerate stars.

1. INTRODUCTION

White-dwarf stars, the most common endpoint of stellar evolution, present a wide variety of spectral appearances, which reflect not only the range of effective temperatures within which these stars are found, but also the large range of chemical compositions encountered in their atmospheres. Spectral classification systems were introduced early on (Kuiper 1941; Luyten 1952; Greenstein 1960) to differentiate the various types of spectra encountered in these objects. Much of the fascinating early history of this field is summarized by Hearnshaw (1990). A revised, more systematic classification system, now in widespread use, was introduced ten years ago by a consortium of the research community on white-dwarfs (Sion et al. 1983). However, this paper did not include any figures illustrating the range of spectral types and subtypes.

Compendia of white-dwarf optical spectra, which outlined the classification system in use, have been published by Greenstein (1958, 1960) and Kaler (1989), but are based solely on photographic spectra. These have now been completely superseded by digital spectra. Modern spectra of many objects in the various spectral classes have frequently been published, but the fact that they are dispersed throughout the literature, as well as their inhomogeneous presentations, tend to limit their use as a scientific tool. Given (i) the current activity surrounding the search for new white-dwarfs, either through colorimetric or proper-motion surveys, or the identification of optical counterparts of X-ray or extreme ultraviolet sources, (ii) the frequency with which white-dwarfs are discovered serendipitously in surveys aimed at other types of objects, as well as (iii) the frequent need—be it for scientific or pedagogical reasons—for illustrative spectra of white-dwarf stars, we deemed it useful to try to collect, in one place, illustrations of the optical spectra associated with the various spectral types encountered among those stars. Readers interested in the spectral properties of white-dwarf stars in the ultraviolet can consult the compilations of Wegner and Swanson (1991) and Wu et al. (1992), which are based on archival *IUE* data.

2. THE SPECTRAL CLASSIFICATION SYSTEM

As discussed previously, the classification system for optical spectra currently in general use is presented in great detail by Sion et al. (1983), and more succinctly by Kaler (1989) and Sion (1992). Because we make extensive use of this system in our atlas, and for completeness, we briefly summarize this system here, together with more recent changes introduced by Greenstein (1986).

In the current system, the letter D indicates a degenerate star, and the second letter indicates the primary spec-

[1]Based, in part, on data obtained at the Kitt Peak National Observatory, National Optical Astronomy Observatories, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation; at the Multiple Mirror Telescope, a joint facility of the Smithsonian Institution and the University of Arizona; and at the German–Spanish Astronomical Center, Calar Alto, operated by the Max-Planck-Institut für Astronomie Heidelberg jointly with the Spanish National Commission for Astronomy.

troscopic signature, *in the optical range,* of the atmosphere: accordingly, DA stands for a star for which the strongest lines are due to hydrogen, DB for a star with He I lines, DO for a star with He II lines, DC for a star with a continuous spectrum, DZ for a metallic-line[2] star (Mg, Ca, Fe), and DQ for a star with atomic or molecular carbon features. All stars which exhibit carbon features in *any part* of their spectrum share the primary symbol Q[3]. The primary spectroscopic signature is often, *but not always,* an indicator of the dominant chemical element in the atmosphere: thus the DA stars generally, *but not always,* have hydrogen-dominated atmospheres, while the DB and DO stars have helium-dominated atmospheres. So do the DZ and DQ stars. The DC stars could have, in principle, either hydrogen- or helium-dominated atmospheres, depending on whether the temperature is high enough for hydrogen lines to be seen.

The additional letters of the system indicate increasingly weaker or secondary spectral features, *observable in any part of the electromagnetic spectrum.* A DAZ star would thus be a hydrogen-line star with evidence for weak metal features, whether in the optical or in the ultraviolet range, while a DQAB star would be a star with carbon features which also shows both weaker hydrogen and neutral helium lines. Other secondary letters are reserved for polarized magnetic stars (P), and for magnetic stars showing no detectable polarization (H). The symbol (V) is also suggested for variable stars, but is seen by many as a photometric index. Its use remains optional. X indicates a peculiar or unclassifiable spectrum, E the presence of emission lines, while ? and : indicate uncertain classifications.

Finally, the digit at the end is an effective-temperature indicator introduced by Sion et al. (1983). It has usually been assigned on the basis of color temperatures determined from either $(G-R)$, $(b-y)$, or $(B-V)$ and calibrated from model-atmosphere calculations. The index corresponds to $50{,}400/T_{\rm eff}$. The very hottest degenerate stars, the PG 1159 stars, have on that scale a temperature index of 1.[4] Greenstein (1986) and Greenstein and Liebert (1990) have refined this temperature sequence by introducing a + sign, which is replaced here by half-integers in order to make this refinement compatible with the upcoming new edition of the 1987 McCook and Sion *Catalog of Spectroscopically Identified White Dwarfs.* Thus, on this expanded system, the sequence of DA stars would run DA1, DA1.5, ..., DA4, DA4.5, DA5, ..., all the way to the coolest hydrogen-line stars at DA13 (Greenstein 1986). A DA4 star would have $11{,}860\ {\rm K} \lesssim T_{\rm eff} \lesssim 13{,}340$ K, while a DA4.5 (or DA4.5$\pm$0.25) star would have $10{,}610\ {\rm K} \lesssim T_{\rm eff} \lesssim 11{,}860$ K, etc...

We have, for this atlas, taken the occasional liberty of readjusting this index for objects for which the latter conflicted with effective temperatures obtained from fits to the line spectrum or energy distribution. Furthermore, this classification system does not yet incorporate a means of distinguishing stars with higher or lower than average surface gravities. Rather, all stars which have sufficiently broad lines that it is likely the surface gravity exceeds $\log g=7$ are eligible for the D classification; the choice of $\log g=7$ is somewhat arbitrary, as the hottest white-dwarfs merge into the hot sdO stars at temperatures $\geqslant$100,000 K (Greenstein and Sargent 1974).

3. THE SPECTROSCOPIC DATABASE

The project makes extensive use of archival spectroscopic data, obtained over the years by numerous investigators with different instrumental setups and telescopes, and kindly made available to us for this effort. Because of this, the database remains, to some extent, inhomogeneous. However, given the quality of existing data, the difficulty of justifying observing time on large telescopes, and the faintness of most white-dwarfs, it was deemed highly unrealistic to attempt to reobserve most or all of the stars discussed here with a unique telescope and setup, as was done for the recent atlas of optical spectra of normal stars of Jacoby, Hunter, and Christian (1984), and that of OB stars of Walborn and Fitzpatrick (1990) in these *Publications.*

This atlas is based on five major sources of spectroscopic material: a fair fraction of the spectroscopic data presented here was obtained with the Double Spectrograph system attached to the 5-m Hale Telescope. In most cases, separate blue and red data were obtained. The data set is presented summarily by Greenstein (1986), and is discussed in more detail by Greenstein and Liebert (1990). Additional material was collected as well over the years at the Steward Observatory 2.3-m telescope, equipped with an Intensified Blue Reticon and, more recently, with blue-sensitive CCD detectors. The resolution of these data varies between ~2.5 and ~6 Å. Material was also obtained at the Kitt Peak National Observatory 2.1-m telescope, with the Gold Spectrograph and Intensified Image Dissector Scanner, and kindly provided by G. Wegner. The data displayed cover the 3300–6900 Å region, at a resolution of ~17 Å. We also make use of ~1 Å resolution data obtained at the MMT telescope, and kindly made available by S. J. Kenyon, which cover the 3750–4650 Å region, as well as of medium-resolution (1.5–3.5 Å) data obtained with the Calar Alto 3.5-m telescope, and kindly provided by K. Werner.

Our spectroscopic material is presented here in the form of figures for each spectral type and subtype. In addition, tables give the common name, as well as the white-dwarf name from the compilation of McCook and Sion (1987). When a star is not listed in that catalog, its white-dwarf

[2]The word "metal" is used here in its usual astronomical sense, and designates chemical elements of atomic weight larger than that of helium. Note that in the white-dwarf classification scheme, carbon is treated distinctly from the other heavy elements.

[3]Because of the great strength of carbon features at ultraviolet wavelengths for some stars with DC optical spectra, the DQ classification was the only case where features outside of the optical spectrum were taken into account in the Sion et al. (1983) system to assign a primary spectral type. Ultraviolet spectra are not otherwise discussed in this paper.

[4]Note that the temperature index 0 (zero) was introduced by Sion et al. (1983) for the very hottest stars. For a variety of reasons, however, it has not found general use in the community. We will thus refrain from using it here as well.

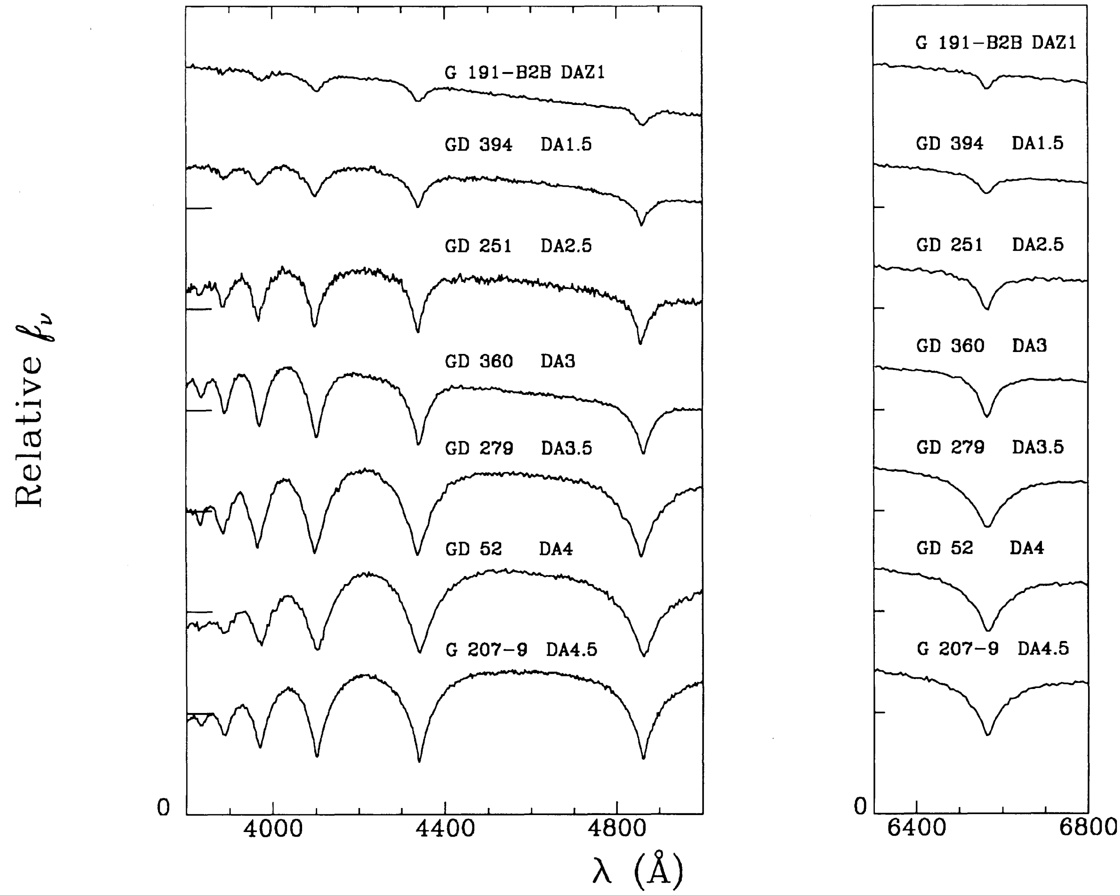


FIG. 1—Optical spectra of stars at the hot end of the DA sequence (Table 1). The blue region is in the left panel, Hα in the right panel. The stars are ordered with decreasing effective temperature from top to bottom. The spectra are characterized by strong Balmer lines, generally visible up to H8 or H9. In this figure, and those that follow, the spectra are shifted vertically for clarity; the zero level of the lowermost plot is always the bottom of the figure. Plots above the lowermost one have zero points indicated by the various long tick marks.

name has nevertheless been constructed and is included in parentheses. The spectral type follows, mainly from McCook and Sion, but taking into account—when available—the later reclassifications of Greenstein (1986) and Greenstein and Liebert (1990), or other supplementary information. Finally, the notes give the reference for the spectral type for the main types (i.e., DA, DB, etc. ...) while, for the subtypes (i.e., DAB, DBA, DBZ, etc. ...), we tried, as much as possible, to refer to the original spectroscopy or spectrophotometry of each object, as well as to later work deemed particularly significant from a spectroscopic point of view.

4. HYDROGEN-LINE WHITE DWARFS: THE DA STARS

4.1 Classical DA Stars

White dwarfs with hydrogen lines are the most common degenerate stars observed, and they account for the majority of the spectroscopically confirmed white-dwarfs cataloged by McCook and Sion (1987). They are found between ~5000 K, the visibility cutoff for hydrogen lines, and ~80,000 K. While hydrogen lines are potentially visible upward of ~100,000 K, there are few or no reported DA stars with such high temperatures. The optical spectra of DA stars are characterized by the presence of ubiquitous, heavily broadened Balmer lines. The strength of these lines peaks near 12,000 K at log $g \sim 8$, in the DA4 subclass. At low temperatures, the Balmer lines become sharper and weaker; for the lowest-temperature DA stars (beyond DA9), only Hα remains visible, and stars for which only lower signal-to-noise ratio (S/N) or blue wavelength spectra exist could have easily been misclassified as DC. For temperatures higher than 12,000 K, on the other hand, the lines become increasingly shallow, with broad, extensive wings. This progression is illustrated in Figs. 1 and 2, where both the blue region (3800–5000 Å) of the spectrum and Hα are shown for the full range of effective temperatures. In DA stars earlier than ~DA6, the last visible Balmer line near the ionization limit—a useful indicator of the electron density in the photosphere—is typically the 2–9 or 2–10 transition. In most DA stars, no other features are observed in the optical spectrum, a result understood in terms of the rapid settling of elements heavier than hydrogen in the intense gravitational field of degenerate stars. For classical DA stars, this absence of lines from helium or

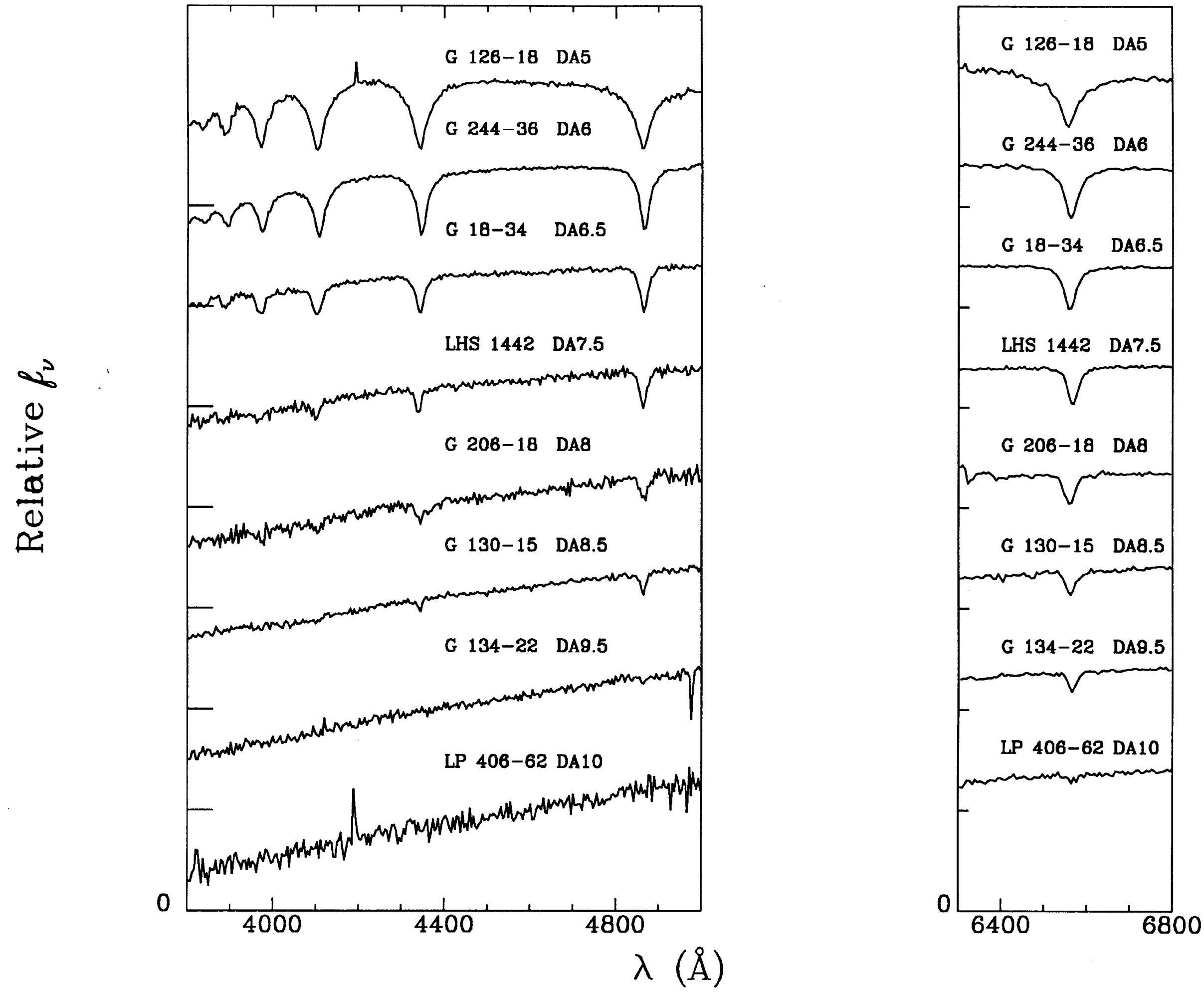


FIG. 2—Same as Fig. 1, but for the cool end of the DA sequence.

heavier elements lead to underabundances of these elements by factors of at least 100 with respect to the solar values.

Note that high-dispersion work on several bright DA white-dwarfs has revealed additional information which is not apparent in the slightly lower-dispersion spectra displayed in Figs. 1 and 2. In particular, G 191-B2B, the hottest DA star displayed, has been shown by Reid and Wegner (1988) to have an emission core at Hα in high-resolution (0.55 Å) spectra. Furthermore, at lower effective temperatures, several DA stars show very narrow NLTE Hα cores, not apparent in our data, from which rotational velocities can be deduced (Pilachowski and Milkey 1987, and references therein).

While it has long been thought that DA stars showed *only* hydrogen lines, and while this is still true for the vast majority of them, recent work has uncovered occasional presence of traces of helium in the spectra of some of these stars. When the helium is in the form of He II, they are called DAO stars; if helium is neutral, these objects are called DAB stars.

4.2 The DAO Stars: DA Stars with Traces of Ionized Helium

The spectra of these stars are characterized by broad and shallow Balmer lines of normal strength for the temperature, together with a sharper He II λ4686. The prototype of the class, HZ 34, was first identified by Koester et al. (1979) as being rather different from the helium-rich DO stars like HZ 21 (see Sec. 5), with which it was previously lumped. No other He II lines are seen in the spectrum. Studies of both the hot end of the DA sequence by Holberg et al. (1989) and Wood and Bergeron (1993), and very old planetary nebulae central stars (Napiwotzki and Schönberner 1991, 1993), have recently turned up several new DAO stars. Observed at high enough S/N, the majority of the hottest DA stars may show traces of He II. Spectra for a sample of these objects are shown in Fig. 3. Note that the lines of HZ 34 appear narrower than those of the remaining DAO stars in Fig. 3; it may well be that the prototype has a surface gravity below 7.0, and therefore should not be classified as a white-dwarf.

TABLE 1
The Sample of DA White Dwarfs

Name	Catalog Name	Sp. Type	Ref.
G 191-B2B	WD 0501+527	DAZ1	*a*
GD 394	WD 2111+498	DA1.5	*b*
GD 251	WD 2331+290	DA2.5	*c*
GD 360	WD 1713+332	DA3	*c*
GD 279	WD 0148+467	DA3.5	*c*
GD 52	WD 0348+339	DA4	*c*
G 207-9	WD 1855+338	DA4.5	*c*
G 126-18	WD 2136+229	DA5	*c*
G 244-36	WD 0148+641	DA6	*c*
G 18-34	WD 2207+142	DA6.5	*c*
LHS 1442	WD 0243−026	DA7.5	*c*
G 206-18	WD 1811+327B	DA8	*c*
G 130-15	WD 2347+292	DA8.5	*c*
G 134-22	WD 0213+427	DA9.5	*c*
LP 406-62	WD 0102+210A	DA10	*c*

[a] DA1.5 in Greenstein and Liebert (1990), but a DAZ1 classification would be more appropriate in view of the confirmed high effective temperature (e.g., Finley, Basri, and Bowyer 1990), and presence of metal features in the *ultraviolet* spectrum.

[b] DA3.5 in Greenstein and Liebert (1990), but DA1.5 more in line with the high effective temperature assigned by Bergeron, Saffer, and Liebert (1992).

[c] Spectral type from Greenstein and Liebert (1990).

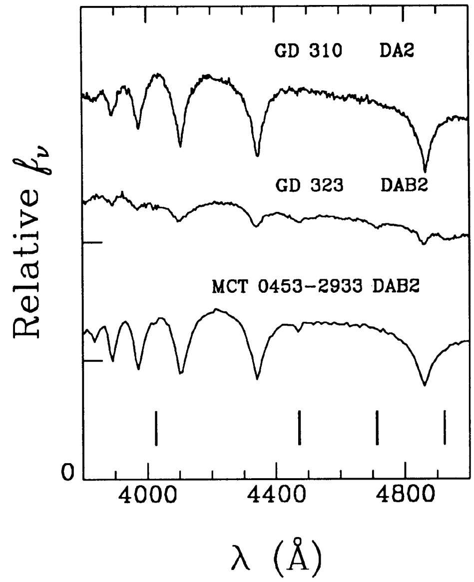


FIG. 4—Optical spectra of two DAB stars (Table 2): GD 323 and MCT 0453−2933. These are degenerate stars whose spectrum is dominated by Balmer lines, but which show weaker He I features, especially He I λ4471. The spectrum of the normal DA2 star GD 310 (top), of similar temperature, is also shown. Tick marks indicate the position of He I $\lambda\lambda$4026, 4471, 4713, and 4921.

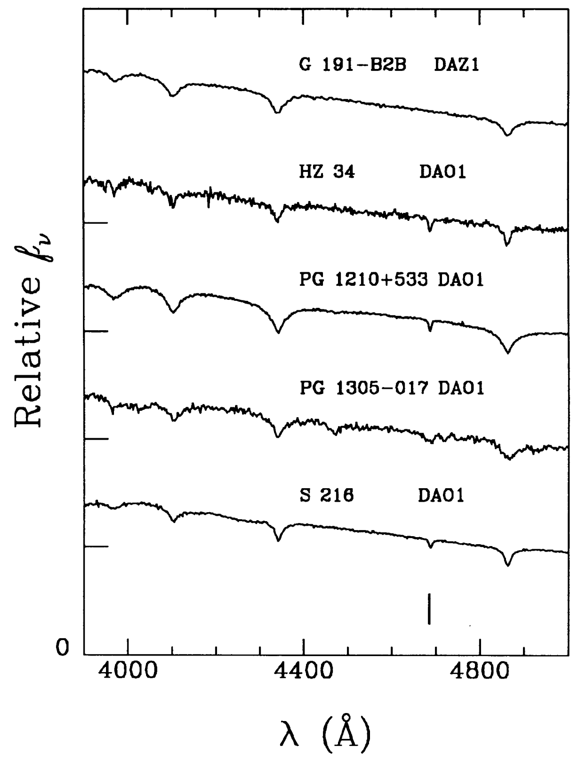


FIG. 3—Optical spectra of four DAO stars (Table 2): HZ 34, PG 1210+533, PG 1305−017, and S 216. These are hot degenerate stars whose spectrum is dominated by Balmer lines, but which show a weak He II λ4686 feature. Note that PG 1305−017 shows weak He I features as well. The spectrum of the normal (DAZ1) star G 191-B2B (see Fig. 1), is also shown. Tick mark indicates the position of He II λ4686.

4.3 The DAB Stars: DA Stars with Traces of Neutral Helium

The first white-dwarf observed to have both hydrogen and neutral helium lines is GD 323, discovered independently by Oke et al. (1984) and Liebert et al. (1984), and analyzed in the latter paper and in Koester (1989, 1991). It displays broad and shallow Balmer lines, together with He I $\lambda\lambda$4471, 4921. It is the prototype of the DAB class, and its spectrum is illustrated in Fig. 4. The prototype may well be unrepresentative of the class, as other known DAB stars (Wesemael et al. 1993; Jordan et al. 1993) have sharper Balmer lines, as illustrated in Fig. 4. Yet another, possibly different, DAB star which was reported by Holberg et al. (1990) has only a very weak He I λ4471 feature, which was detected in high signal-to-noise spectra of the object. However, this feature has not been detected in subsequent observations (e.g., Kidder et al. 1992). The known objects in this class appear to cluster around $T_{\rm eff}\sim$25,000 K.

4.4 The DAZ Stars: DA Stars with Traces of Metals

Only one DA star, the cool star G 74-7, is currently known to display metal features in its *optical* spectrum (Lacombe et al. 1983). Its spectrum, shown in Fig. 5, is characterized by the usual Balmer lines of normal strength for its temperature ($T_{\rm eff}\sim$7200 K), together with a narrow Ca II feature. This object is classified DAZ.

Note that the DAZ classification may be applied as well to the several additional hot, hydrogen-atmosphere stars which are known to display photospheric metal features in their *ultraviolet spectrum:* G 191-B2B, the hot DA star

TABLE 2
The Sample of DAO, DAB, and DAZ White Dwarfs

Name	Catalog Name	Sp. Type	Ref.
	The DAO Stars		
HZ 34	WD 1253+378	DAO1	*a*, *b*
PG 1305-017	WD 1305−017	DAO1	*c*
PG 1210+533	WD 1210+533	DAO1	*b*, *c*
S 216	(WD 0441+463)	DAO1	*d*
	The DAB Stars		
GD 323	WD 1302+597	DAB2	*e*
MCT 0453-2933	(WD 0453−295)	DAB2	*f*
	The DAZ Star		
G 74-7	WD 0208+396	DAZ7	*g*

[a] Koester, Liebert, and Hege (1979)
[b] Wesemael, Green, and Liebert (1985)
[c] Holberg et al. (1989)
[d] Napiwotzki (1992)
[e] Oke, Weidemann, and Koester (1984); Liebert et al. (1984)
[f] Wesemael et al. (1993)
[g] Lacombe et al. (1983)

displayed in Figs. 1 and 4, and Feige 24 are the most notable examples, with various features of C, Si, N, O, and Fe detected in *IUE, Hubble,* and sounding-rocket spectra in the FUV and EUV ranges (Bruhweiler and Kondo 1981, 1983; Dupree and Raymond 1982; Bruhweiler and Feibelman 1993; Sion et al. 1992; Wilkinson et al. 1992). Further discoveries of features due to heavy elements, as well as helium, are currently being reported from *ROSAT* and *EUV Explorer* missions.

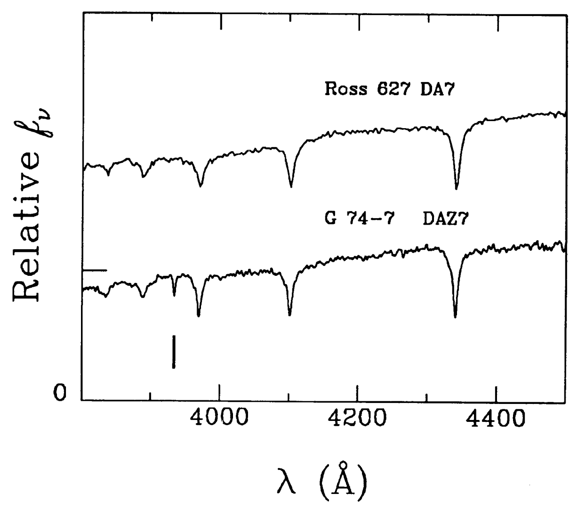


FIG. 5—Optical spectrum of the DAZ star G 74-7 (Table 2). This cool star has a spectrum dominated by Balmer lines, together with a weak Ca II λ3933 feature, indicated by a tick mark. The λ3968 component is blended with Hϵ λ3970. The spectrum of the normal DA7 star Ross 627 (Liebert and Wehrse 1983), of similar temperature, is also shown.

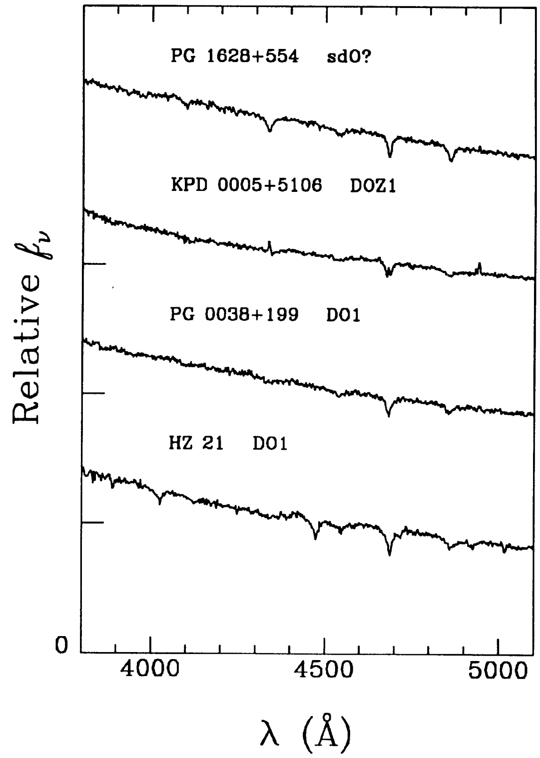


FIG. 6—Optical spectra of DO stars (Table 3). The bottom three stars shown form an approximate temperature sequence, with the prototype of the cool DO stars, HZ 21, at the bottom. It shows both He I λ4471 and He II λ4686, as well as other He II lines. PG 0038+199 is a so-called hot DO star, with no He I, strong λ4686, as well as weak shallow lines from the n=4 He II series. KPD 0005+5106 shows He II λ4686 with an emission core, as well as emission features recently identified by Werner and Heber (1992) as O VIII lines. The top object, PG 1628+554, appears very similar to the hot DO stars, but—with its slightly narrower lines—is currently thought to be a lower gravity sdO object.

5. THE HOT HELIUM-LINE STARS: THE DO STARS

At high effective temperatures, the spectra of helium-atmosphere white-dwarfs are dominated by ionized helium lines and these objects are called DO stars (Fig. 6). They are generally found above 45,000 K, but their high-temperature boundary is ill defined, but is likely to be around 100,000 K. Wesemael et al. (1985) distinguished two subclasses of DO stars. The cool DO stars ($T_{\rm eff}$~45–

TABLE 3
The Sample of DO White Dwarfs

Name	Catalog Name	Sp. Type	Ref.
HZ 21	WD 1211+332	DO1	*a*
PG 0038+199	(WD 0038+199)	DO1	*b*
KPD 0005+5106	WD 0005+511	DOZ1	*c*
PG 1628+554		sdO?	*b*

[a] Wesemael, Green, and Liebert (1985)
[b] Saffer (1992)
[c] Downes, Liebert, and Margon (1985), Werner and Heber (1992)

TABLE 4
The Sample of DB White Dwarfs

Name	Catalog Name	Sp. Type	Ref.
PG 0112+104	WD 0112+104	DB2.5	*a*
GD 358	WD 1645+325	DB2	*a*
Feige 4	WD 0017+136	DB3	*b*
GD 233	WD 2130−047	DB4	*b*
GD 124	WD 1046−017	DB5	*b*
GD 408	WD 0002+729	DB4	*b*
G 226-32	WD 0000−170	DB4	*b*
G 119-47	WD 1056−345	DB5	*b*
G 188-27	WD 2147+280	DB4.5	*a*
GD 392	WD 2058+342	DB5	*a*

[a] Revised spectral type from Greenstein and Liebert (1990)
[b] Spectral type from McCook and Sion (1987)

70,000 K) show conspicuous He I features and very strong He II λ4686; HZ 21 (Fig. 6) is the prototype of that subclass. The hot DO stars ($T_{\rm eff} \geqslant 80{,}000$ K) show only He II lines, as shown in the spectrum of PG 0038+199. λ4686 remains strong, and additional, broader He II lines from the $n=4$ series are generally seen as well. The prototype of these objects is PG 1034+001. In Fig. 6, we also show for contrast, and as a *caveat*, the spectrum of PG 1628+554. This star is very similar to the hot DO group in showing only relatively strong He II lines, though the $n=4$ series transitions are significantly sharper. Although not obvious from inspection of its spectrum, a preliminary analysis suggests that this star has $\log g \lesssim 7.0$, so that it does not qualify for the white-dwarf designation according to the arbitrary definition of Sec. 2. At very high temperatures, the white-dwarfs clearly merge with the hot subdwarfs and central stars of planetary nebulae.

Wesemael et al. (1985) also delineated a still hotter ($T_{\rm eff} \gtrsim 100{,}000$ K; Werner 1992) subgroup of hydrogen-poor stars with gravities approaching or exceeding $\log g = 7$; these so-called PG 1159 stars have features due to CNO ions as well as helium, and are therefore discussed separately (Sec. 10). Shown in Fig. 6 is a hybrid object, KPD 0005+5106 (Downes et al. 1985), which appears to be intermediate between the hot DO and the PG 1159 classes; it has a predominantly He II spectrum, but with unique emission lines attributed to highly ionized species (Werner and Heber 1992).

In principle, there could be a cooler class of helium-rich star, which might be called DBO, in which both He I and He II lines appear, but with the former having the greater strengths. While lower gravity, helium-rich subdwarfs exist with such spectra, a white-dwarf with these characteristics has not yet been found. More generally, there is as yet no known helium-rich white-dwarf within a $T_{\rm eff}$ range of roughly 45,000 K > $T_{\rm eff}$ > 30,000 K (Liebert et al. 1986). At 45,000 K, the He II features are dominant in the spectrum, while at 30,000 K, He II can no longer be detected.

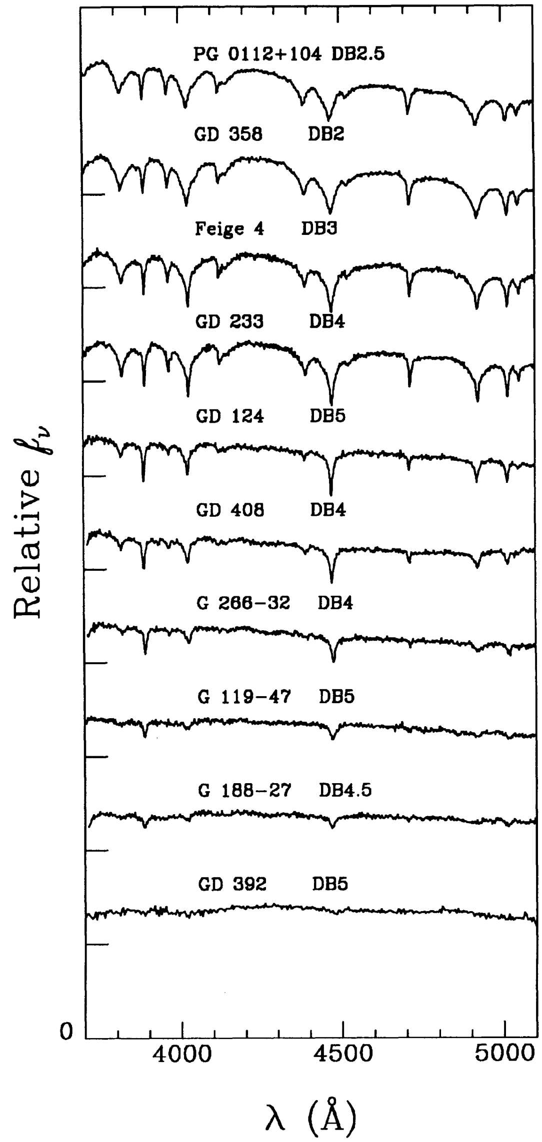


FIG. 7—Optical spectra of classical DB stars (Table 4). The stars shown form an approximate temperature sequence, with the hottest one —PG 0112+104, the hottest known DB star—at the top and the coolest one, GD 392—a DB5 star with barely visible He I λ4471—at the bottom.

6. THE COOL HELIUM-LINE STARS: THE DB STARS

6.1 The Classical DB Stars

The classical DB stars show the rich spectrum of the He I ion in the optical range, with nothing else. The reported range goes from DB2 for PG 0112+104 and GD 358, the hottest reported DB stars (Thejll et al. 1991), to DB5 for stars with barely visible λ4471 in the blue spectrum, and somewhat stronger $\lambda\lambda$5876, 6678 in the red spectrum. At the cool end of their sequence, the coolest DB stars merge smoothly with the helium-rich DQ stars, with traces of carbon in their spectra. This sequence is illustrated in Fig. 7, where stars are displayed in order of

TABLE 5
The Sample of DBA, DBZ, DBAZ, and DBQ White Dwarfs

Name	Catalog Name	Sp. Type	Ref.
	The DBA and DBAZ Stars		
LP 475-242	WD 0437+138	DBA4	*a*
GD 243	WD 2253−062	DBA4	*a*
GD 61	WD 0435+410	DBAZ3	*b*
GD 378	WD 1822+410	DBAZ4	*c*
G 200-39	WD 1425+540	DBAZ4	*d*
	The DBZ Stars		
GD 40	WD 0300−013	DBZ4	*e*
CBS 78	WD 0838+375	DBZ5	*f*
	The DBQ Stars		
G 218-8	WD 0038+555	DBQ5	*g*
LDS 678A	WD 1917−077	DBQA5	*h*
L 791-40	WD 2317−173	DBQA5:	*i*

[a] This work.

[b] Wegner and Nelan (1987) for the hydrogen lines; Sion, Aannestad, and Kenyon (1988) for the Ca II lines.

[c] Greenstein (1986) for the hydrogen lines; Sion, Aannestad, and Kenyon (1988) for the Ca II lines.

[d] Liebert et al. (1979b) for the hydrogen lines; Kenyon et al. (1988) for the Ca II lines.

[e] Wickramasinghe et al. (1975)

[f] Sion et al. (1986)

[g] Greenstein (1986); Greenstein and Liebert (1990). Carbon ultraviolet spectrum discussed by Wegner (1981c).

[h] Greenstein (1986); Greenstein and Liebert (1990). Carbon ultraviolet absorptions discussed by Wegner (1981b) and Oswalt et al. (1991).

[i] Greenstein (1986); Greenstein and Liebert (1990). Carbon ultraviolet absorptions discussed by Koester et al. (1982).

decreasing line strength. The temperature index of Table 4 does not follow this order perfectly, and some of these assignments could be inaccurate. The complex variation of He I line strengths and especially of their profiles presents a challenge to find a detailed set of atmospheric structures which would reproduce the observed spectra. Readers interested in examining additional DB spectra should consult Wegner and Nelan (1987).

6.2 DB Stars with Impurities: The DBA, DBAZ, DBZ, and DBQ Stars

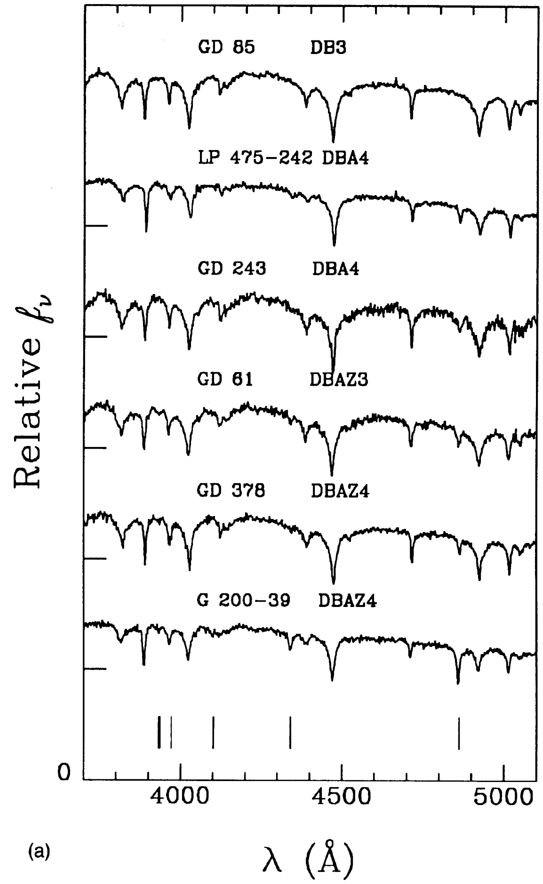
A fair fraction of the DB stars show impurities in their spectra, in the form of hydrogen, metals, or both. The prototypes of the DBA class are LDS 785 A (Wickramasinghe and Whelan 1977) and G 200-39 (Liebert and Strittmatter 1977). The latter has the strongest hydrogen lines in the class (Liebert et al. 1979b). Several such objects have since been found, in particular in the PG survey (Shipman et al. 1987), but also among previously classified DB stars as they have been subjected to more accurate spectroscopy. Recently, Kenyon et al. (1988) showed that the prototype G 200-39 also exhibits weak Ca II lines, which now make this object a DBAZ4 star. Two additional such objects were found by Sion et al. (1988), and all three are shown in Fig. 8. Ionized calcium had been known to exist before in at least one DB star, which formed the DBZ subclass: GD 40, the prototype, was discovered by Wickramasinghe et al. (1975). A second, and similar object, CBS 78, has been found recently by Sion et al. (1986), and the spectra of both stars in that class are shown in Fig. 9.

Figure 10 presents spectra for a DBQ star, G 218-8, as well as two DBQA stars, LDS 678A and L 791-40. The spectrum of the former is characterized by a weak He I λ5876 feature and probable, greatly broadened C_2 features. Its ultraviolet spectrum is rich in C I lines (Wegner 1981c). The other two objects have similar optical spectra: Greenstein and Liebert (1990) comment on the waviness of the spectrum of LDS 678A, attributed to greatly broadened C_2 features, and report the C_2 4670 Å band with a strength of a few Angströms. The spectrum shows, in addition, noticeable He I λ4471 as well as weak Hα. The presence of carbon has been confirmed by the ultraviolet features detected with the *IUE* (Wegner 1981b; Oswalt et al. 1991). L 791-40 has a similar optical spectrum, with He I, Hα as well as Hβ. This object also exhibits evidence for carbon in its ultraviolet spectrum (Koester et al. 1982).

7. COOL HELIUM-RICH STARS WITH METALLIC LINES: THE DZ STARS

Helium-rich atmospheres too cool to show lines of He I—i.e., at or below DB5 (about 9000 K)—but which still show metal features, are called DZ star. Spectra for several such stars are shown by Liebert et al. (1987) and Sion et al. (1990), and Figs. 11 and 12 show a sample of these spectra. Like their hotter DBZ counterparts, their spectra show the Ca II H and K doublet $\lambda\lambda$3933, 3968, occasionally with Mg I λ3835 and Fe I features such as λ3730. The DZ stars in Fig. 11 are ordered in approximate order of decreasing temperature, but the strength of the Ca II lines is not a monotonic function of temperature, because the metal abundance can vary from one object to the next. High-resolution or high S/N ratio is required to identify the objects with the weakest Ca II lines. The heavily blanketed star LP 701-29 (Dahn et al. 1978) is the coolest such object known, and is the only known case where Ca I λ4226 appears stronger than the Ca II doublet. Nearly all other features are hopelessly blended at bluer wavelengths; there is a decisive drop in the flux level below ~4200 Å (Kapranidis and Liebert 1986).

Four additional objects are shown in Fig. 12. GD 401 has a very strong Ca II doublet ($W=131$ Å; Greenstein et al. 1977; Liebert et al. 1979a), Ca I λ4226, but no hydrogen. It has been analyzed by Cottrell and Greenstein (1980b). Ross 640, analyzed by Liebert (1977a) and Cottrell and Greenstein (1980a), shows strong Mg I λ3835 and Ca II features, as well as a weak Hα ($W=6$ Å), which is not shown here. The cooler DZ7.5 star vMa 2 shows strong Ca II, and Fe I and Mg I blends (Greenstein 1960), as well as a weak Ca I λ4226 line. Finally, G 165-7, discovered by Hintzen and Strittmatter (1974) and analyzed by Wehrse and Liebert (1980) shows an unusually rich spectrum of Fe I, Mg I, Ca I, and Ca II features in the blue, as well as unique Mg I λ5175, Fe I λ5267, and Na I λ5892



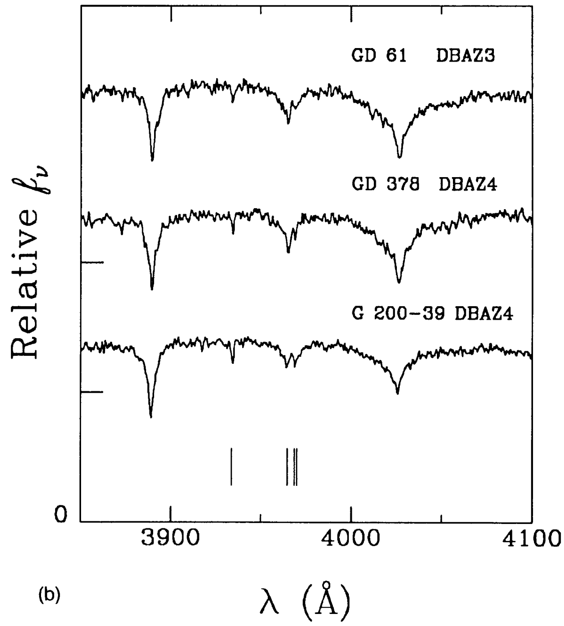


FIG. 8—(a) Optical spectra of DB stars with impurities (Table 5): LP 475-242 and GD 243 are two DBA stars, i.e., DB stars with traces of hydrogen, while GD 61, GD 378, and G 200-39 are DBAZ stars, i.e., DBA stars with weak Ca II as well. Thin tick marks indicate the location of the Balmer lines of hydrogen, Hβ to Hϵ, the latter blended with Ca II λ3968 in DBAZ stars. Thick tick mark indicates the location of the Ca II λ3933 component of Ca II, detected in the DBAZ stars. GD 85 (top plot) is a classical DB 3 star, shown here for comparison. (b) The 3850–4100 Å region in the DBAZ stars GD 61, GD 378, and G 200-39. Tick marks indicate the location, from left to right, of Ca II λ3933, He I λ3965, Ca II λ3968, and He λ3970. The latter two are blended in these spectra.

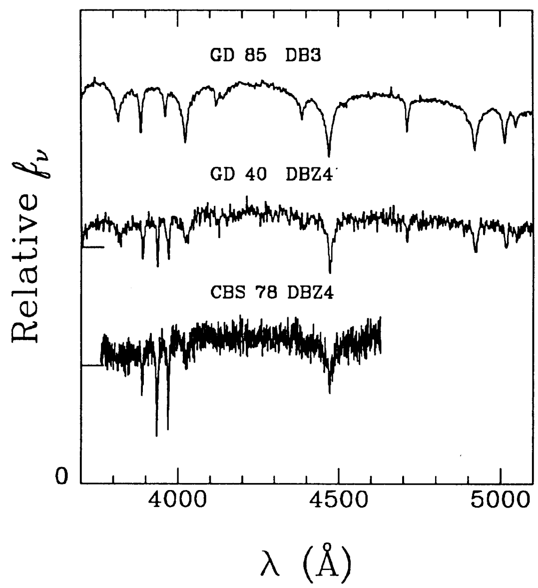


FIG. 9—Optical spectra of two DBZ stars (Table 5), GD 40 and CBS 78, with Ca II but no trace of hydrogen in their spectra. The Ca II λ3968 component can be blended with the weaker He I λ3965. GD 85 (top plot) is a classical DB3 star, shown here for comparison. The shape of the continuous energy distribution of CBS 78 has been established by assuming that it is similar to that of GD 40.

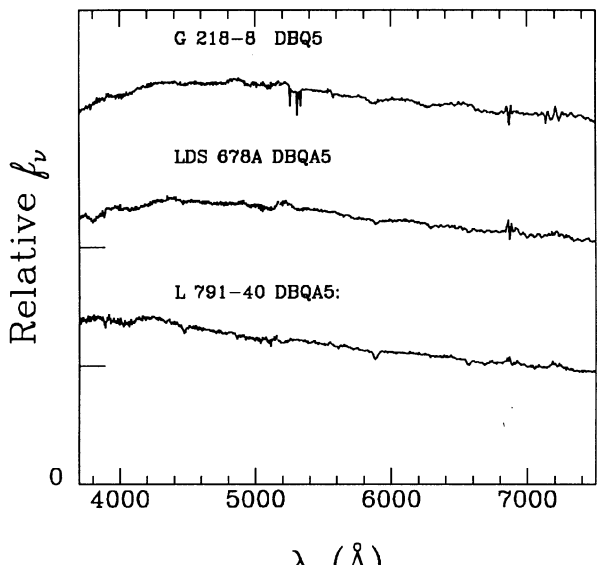
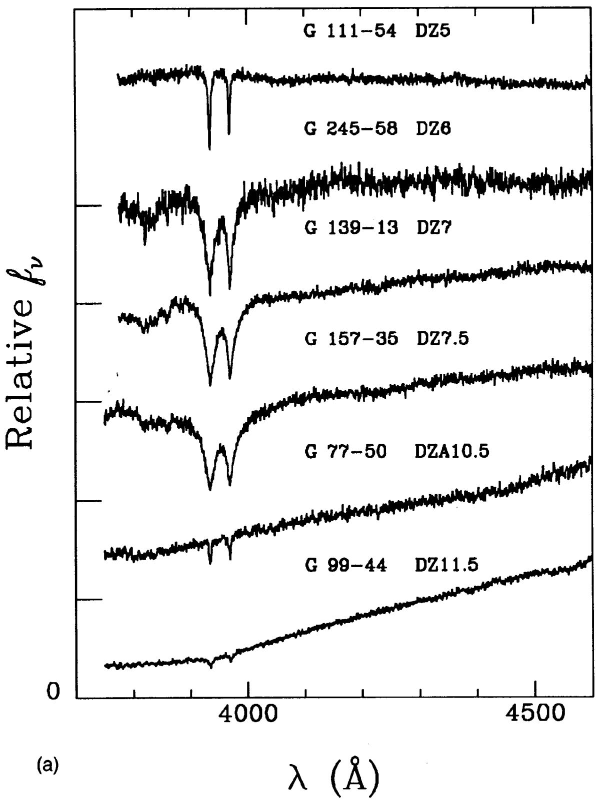


FIG. 10—Optical spectra of three DBQ stars (Table 5). G 218-8, at the top, shows weak He I, together with broadened C_2 features, but no H I. The other two, LDS 678A and L 791-40, are classified DBQA. Both have weak He I $\lambda\lambda$4471, 5876 and Hα features, and a broad, shallow C_2 band at 4670 Å. G 218-8 and LDS 678A both show strong C I features in the ultraviolet (Wegner 1981b,c; Oswalt et al. 1991). The spurious dips near 5300 Å are associated with the presence of a dichroic filter to separate grating orders, while the glitches near 6800 and 7200 Å are due to an incomplete correction for atmospheric O_2.



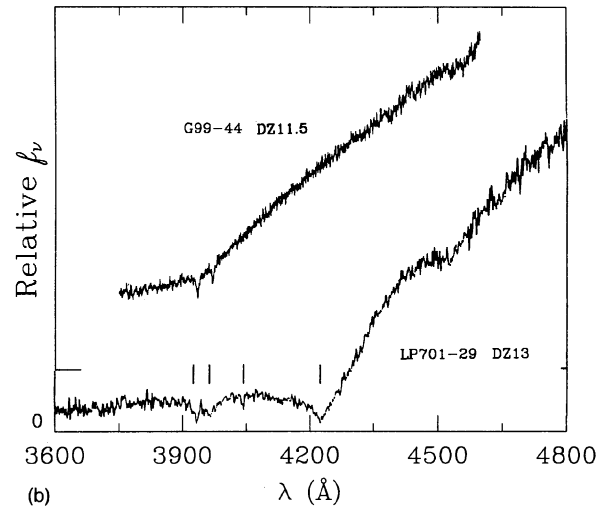


FIG. 11—(a) Optical spectra of DZ stars (Table 6). These cool, helium-rich objects show prominent Ca II H and K $\lambda\lambda$3933, 3968, with occasionally Mg I λ3835, and Fe I λ3730. The stars shown form a temperature sequence, with the hottest star (DZ5) at the top and the coolest one (DZ11.5) at the bottom. The shapes of the energy distributions were redressed on the basis of those of stars of roughly the same effective temperature. (b) Spectrum of the heavily blanketed star LP 701-29, together with that of G 99-44, already shown in Fig. (a). The tick marks indicate the location of, from left to right, the Ca II H and K, Fe I λ4045, and Ca I λ4226 features.

features in the red (not shown here; see Wehrse and Liebert 1980).

8. COOL HELIUM-RICH STARS WITH CARBON FEATURES: THE DQ STARS

The optical spectra of these cool helium-rich stars, shown in Fig. 13(a), are generally characterized by the presence of bands of molecular carbon, most notably the Swan (2,0) (λ4382), (1,0) (λ4737), (0,0) (λ5165), and (0,1) (λ5635) bands. Some objects also show the bands of the Deslandres–d'Azumbuja system ($\lambda\lambda$3600, 3852, 4102, ...) in their blue spectra. Others, such as the fairly hot DQ star G 47-18 [Fig. 13(a)], show C I features as well. Readers interested in examining additional DQ spectra should consult Wegner and Yakovich (1984).

The peculiar star LHS 1126 [Fig. 13(a) and 13(b)] represents an apparent extension to cool temperatures of the DQ sequence, with its spectrum—characterized by a shallow absorption feature around 5000 Å—explained in terms of heavily shifted and broadened C_2 bands by Liebert and Dahn (1983). The strong bands in ESO 439-162 [Fig. 13(b)], discovered by Ruiz and Maza (1988), are similar to those observed in the polarized star LP 790-29 (Liebert et al. 1978), where the observed shift is attributed to a surface magnetic field of the order 100 MG; a similar field could be responsible for the shift observed in ESO 439-162, although there is currently no polarimetric information available for this object. The similarity of ESO 439-162 to, and differences from, G 99-37 (see Fig. 19) emphasizes the

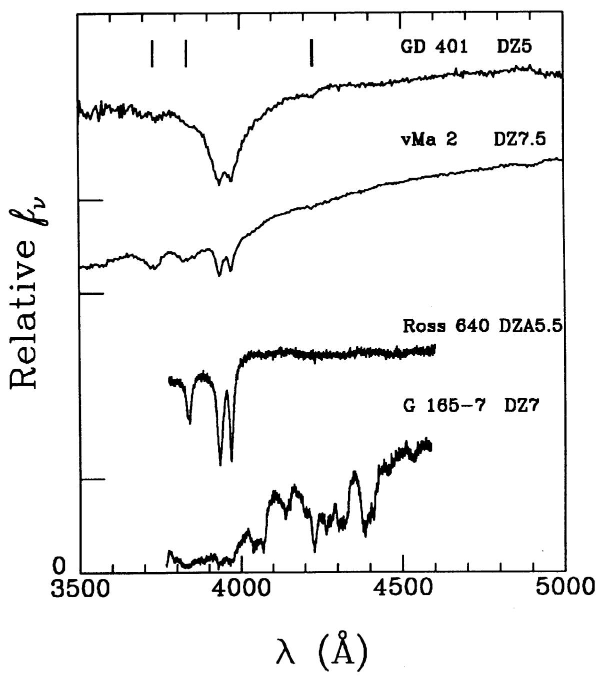


FIG. 12—Optical spectra of additional, interesting DZ stars (Table 6). GD 401 displays the strongest Ca II H and K $\lambda\lambda$3933, 3968 doublet of all DZ stars. vMa 2 and Ross 640 both display strong Mg I λ3835, and the former strong Fe I λ3730 as well. The fourth object, G 165-7, has the richest metallic-line spectrum of all DZ stars. The shape of the energy distribution of that star has not been redressed. Tick marks at the top indicate the location, from left to right, of Fe I λ3730, Mg I λ3835, and Ca I λ4226.

TABLE 6
The Sample of DZ White Dwarfs

Name	Catalog Name	Sp. Type	Ref.
G 111-54	WD 0802+386	DZ5	*a*
G 245-58	WD 0246+735	DZ6	*a*
G 139-13	WD 1705+030	DZ7	*a*
G 157-35	WD 2312−024	DZ7.5	*a, b*
G 77-50	WD 0322−019	DZA10.5	*a, b*
G 99-44	WD 0552−041	DZ11.5	*a*
LP 701-29	WD 2251−070	DZ13	*c*
GD 401	WD 2215+388	DZ5	*d*
vMa 2	WD 0046+051	DZ7.5	*e*
Ross 640	WD 1626+368	DZA5.5	*f*
G 165-7	WD 1328+307	DZ7	*g*

[a] Sion, Kenyon, and Aannestad (1990)
[b] Greenstein and Liebert (1990)
[c] Dahn et al. (1978); Kapranidis and Liebert (1986)
[d] Greenstein et al. (1977); Liebert et al. (1979a)
[e] Greenstein (1960)
[f] Liebert (1977a)
[g] Wehrse and Liebert (1980)

need for spectropolarimetry. We note in passing that LHS 1126 may show additional absorption at 1–2 μm (Lebofsky and Liebert 1986; but see Bergeron et al. 1993).

Also shown in Fig. 14 are spectra of two DQA stars: the first one is G 227-5, near 12,500 K, which has a spectrum dominated by C I lines, together with weaker features of H I (Wegner 1983). The lines of He I, the dominant chemical species in the atmosphere, are weak at best: λ4471 is broad, but could be mostly blends from C I $\lambda\lambda$4461,4478, while He I λ5876 is absent in the red spectrum. Greenstein and Liebert (1990) call it DQAB?, and suggest that its effective temperature could be lower than that assigned by Wegner and Koester (1985) in view of the weakness of the He I lines. The other such star, G 35-26, is a faint degenerate, with a comparable effective temperature (between 11,000 and 14,000 K) but broader and stronger H I lines, and no evidence for He I features (Hintzen and Jensen 1979; Liebert 1983).

TABLE 7
The Sample of DQ White Dwarfs

Name	Catalog Name	Sp. Type	Ref.
G 47-18	WD 0856+331	DQ5	*a, b*
G 171-27	WD 2352+401	DQ5	*c*
G 195-42	WD 0946+543	DQ6	*d*
L 879-14	WD 0435−088	DQ7	*e*
G 87-29	WD 0706+377	DQ8	*f*
Wolf 219	WD 0341+182	DQ8	*e*
LHS 1126	WD 0038−226	DQ?10	*g*
ESO 439−162	(WD 1127−311)	DQH?8	*h*
	The DQA Stars		
G 35-26	WD 0203+207	DQA4	*i*
G 227-5	WD 1728+560	DQAB?4	*j*

[a] McCook and Sion (1987) give DQ6, but DQ5 more in line with the effective temperature of Wegner and Yackovich (1984).
[b] Eggen and Greenstein (1967); Liebert (1977b)
[c] Wegner (1981a)
[d] Wegner and Yackovich (1982)
[e] Greenstein and Matthews (1957)
[f] Eggen and Greenstein (1965)
[g] Liebert and Dahn (1983)
[h] Ruiz and Maza (1988). The large blueward shifts of the C_2 bands observed in this star strongly suggest that it is magnetic, a lower field analog to LP 790-29 (Liebert et al. 1978).
[i] Hintzen and Jensen (1979); Liebert (1983); Thejll et al. (1990). On the basis of the latter, the temperature index could be between 3.5 and 4.5. We assign it a temperature index of 4, while the McCook and Sion (1987) color-based value is 3.
[j] Wegner (1983); Wegner and Koester (1985).

9. WHITE DWARFS WITH TRULY FEATURELESS SPECTRA: THE DC STARS

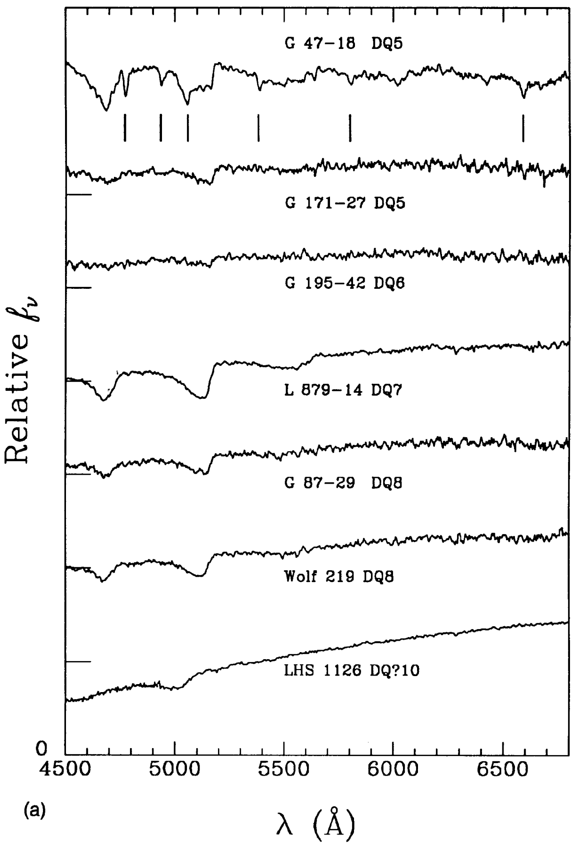
These stars represent one of the most interesting puzzles associated with white-dwarf spectra. The traditional definition of a DC has been a featureless spectrum with no line deeper than 5% of the continuum. Modern, high S/N observations have permitted even weaker features to be detected. Owing mostly to the efforts of Wegner (1981a, 1983), Wegner and Yackovich (1982), and Greenstein (1986), a fair fraction of stars originally classified DC have been reclassified. Many such stars were found to show weak He I lines, making them DB stars, or shallow, broad Swan bands of the C_2 molecule, making them DQ stars. The difficulty in assigning a correct spectral type to the hotter DC stars, near DC 7, is emphasized by Greenstein (1986). Stars such as G 125-3 could thus equally well be cool, DQ stars with a carbon abundance slightly lower than that encountered in the classical DQ stars. Ultraviolet spectra might reveal carbon features.

Other cool DC stars turned out to show a weak Hα line, and these were thus reclassified DA stars. Note that, in such cases, the presence in the spectrum of a hydrogen line does not allow one to infer much about the dominant chemical constituent of the atmosphere: Greenstein (1986) argues, on the basis of the very steep Balmer decrement (i.e., Hα present, but no other Balmer line detected at high signal-to-noise ratio), that these stars are likely to be helium-rich, but this question is far from being resolved (e.g., Bergeron 1988; Ruiz et al. 1993).

Despite these studies at high S/N ratios of the DC sample, true DC stars still remain, especially among the very coolest known white-dwarfs. Several examples of these are shown in Fig. 15.

10. THE PG 1159 STARS

This hot extension of the white-dwarf sequence was first uncovered with the discovery of the pulsating star PG 1159 −035 (GW Virginis) by McGraw et al. (1979a,b), while the recognition of these stars as a fairly homogeneous class of hot white-dwarfs came with the work of Wesemael et al. (1985) on the hot stars in the PG survey. Medium-resolution optical spectra are characterized by an absence of H or He I features, and a very distinctive He II and C IV blend in the 4650–4690 Å region. O VI and additional C IV



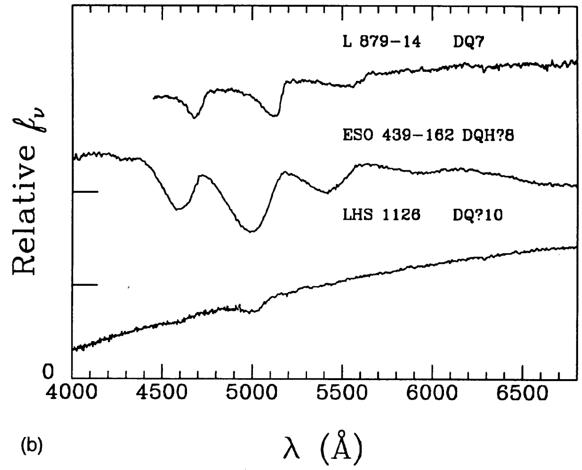


FIG. 13—(a) Optical spectra of DQ stars (Table 7). The C I features identified by Liebert (1977b) are identified by tick marks in the spectrum of G 47-18. The very cool star LHS 1126, at the bottom, represents a likely cool extension of the DQ sequence, out to DQ?10. (b) Optical spectra of two DQ stars with what are thought to be shifted and broadened C_2 bands. The strong bands in ESO 439-162 are likely to be shifted by a magnetic field of ~ 100 MG, while the absorption feature near 4980 Å in LHS 1126 [already displayed in (a)], at the boundary between the blue and red spectrum, is thought to be a greatly broadened and shifted band in the C_2 spectrum at the high densities which characterize the atmosphere of that cool star. L 879-14 is a standard DQ7 star, taken from (a), and shown here for comparison.

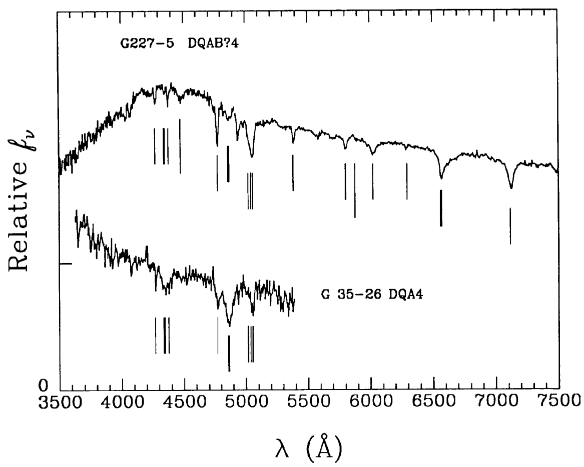


FIG. 14—Optical spectrum of the DQAB?4 star G 227-5 (top), and of the faint DQA4 star G 35-26 (Table 7). The spectrum of the former, as described in Greenstein and Liebert (1990), suffered an instrumental light loss in the violet. For that spectrum, short thin tick marks indicate the C I features reported by Wegner and Koester (1985), short thick tick marks indicate the Balmer lines, and long thin tick marks indicate the location of the uncertain He I features; He I λ4471 could well be due mostly to C I, while λ5876 is absent. For the G 35-26 (bottom) spectrum, thin tick marks indicate the C I features identified by Liebert (1983), while thick tick marks indicate the broad Balmer lines.

lines were also reported in the blue and near-ultraviolet spectra of several objects by Sion et al. (1985).

Werner (1992) has summarized the more definitive work carried out in Kiel on these objects. He proposes to divide the PG 1159 objects into the following three broad groups: The cooler PG 1159 stars, near $T_{\rm eff} \sim 100{,}000$ K, have spectra characterized by the above-mentioned He II and C IV blend entirely in absorption, as are the C IV $\lambda\lambda$5801, 5812 and O VI $\lambda\lambda$3811, 3834 doublets, and the O VI λ5291 complex. This group of stars is called the **A** group. Two such stars, PHL 1025 and PG 1424+535, are shown in Figs. 16 and 17 in several spectral regions. Hotter stars, at or above $T_{\rm eff} \sim 140{,}000$ K, fall in Werner's **E** group, and have emission cores superposed onto the various blends and features. The prototype, PG 1159−035, as well as PG 1520+525 and PG 1144+005, fall into that class. The latter has interesting additional features, as it

TABLE 8
The Sample of DC White Dwarfs

Name	Catalog Name	Sp. Type	Ref.
G 125-3	WD 1917+386	DC?7.5	a
G 187-8	WD 2048+263	DC9	a
LP 406-63	WD 0102+210B	DC12	a
LHS 483	WD 2002−110	DC13	a
Ross 193B	WD 2054−050	DC13	a

[a] Greenstein and Liebert (1990)

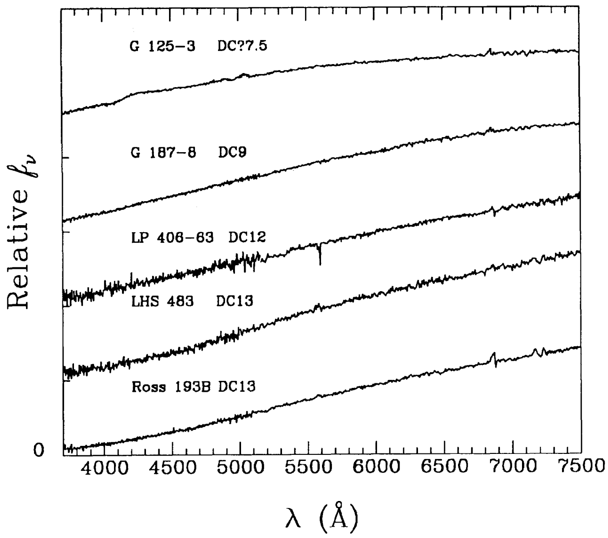


FIG. 15—Optical spectra of DC stars (Table 8). Both the blue and, more interestingly, the red region of the spectrum are completely featureless, with no sign of Hα. The stars are ordered in order of decreasing effective temperatures, from a DC?7.5 star at the top to a DC13 star at the bottom. The former could have, according to Greenstein and Liebert (1990), barely visible, heavily broadened C_2 bands, and could equally well be classified DQ?7.5. The glitches near 5577, 6800, and 7200 Å are due to an incomplete correction for atmospheric O_2 and night-sky lines.

also exhibits the N V doublet $\lambda\lambda$4604, 4620, as well as λ4945 in emission. Most of these stars, with their optical spectra dominated by He II, C IV, and O VI should be classified DOQZ1. Yet another object, H 1504+65 is an extreme PG 1159 star, as its 4650–4690 Å blend consists solely of C IV, with no trace of helium. Its atmosphere is composed of nearly equal amounts of carbon and oxygen, with essentially no hydrogen and helium (Werner 1991). With its optical spectrum dominated by the O VI λ5291 feature, it is best classified as a DZQ1 star. Finally, there exists a low-gravity group of central stars of planetary nuclei, the **lgE** stars, the prototype of which is K 1-16, which display the characteristic PG 1159 spectrum with emission cores, but with generally narrower absorption features. As an illustration of this group, we display in Figs. 16 and 17 the optical spectrum of RXJ 2117.1+3412, the optical counterpart of a soft X-ray source recently discovered in the *EXOSAT XRT* all-sky survey (Motch et al. 1993). Since this object has a surface gravity near $\log g \sim 6$, it is not classified as a white-dwarf, but is nevertheless included here for completeness.

TABLE 9
The Sample of PG 1159 White Dwarfs

Name	Catalog Name	Sp. Type	Ref.
	The **A** Group		
PHL 1025	(WD 0130−196)	DOQZ1	*a, b*
PG 1424+535	WD 1424+534	DOQZ1	*c, d*
	The **E** Group		
PG 1520+525	WD 1520+525	DOQZ1	*c, d*
PG 1159-035	WD 1159−034	DOQZ1	*c, d*
PG 1144+005	WD 1144+004	DOQZ1	*e*
H 1504+65	WD 1501+664	DZQ1	*f, g*
	The **lgE** Group		
RXJ 2117.1+3412			*h*

[a] Demers et al. (1990)
[b] Werner (1992)
[c] Wesemael, Green, and Liebert (1985)
[d] Werner, Heber, and Hunger (1991)
[e] Werner and Heber (1991)
[f] Nousek et al. (1986)
[g] Werner (1991)
[h] Motch, Werner, and Pakull (1993)

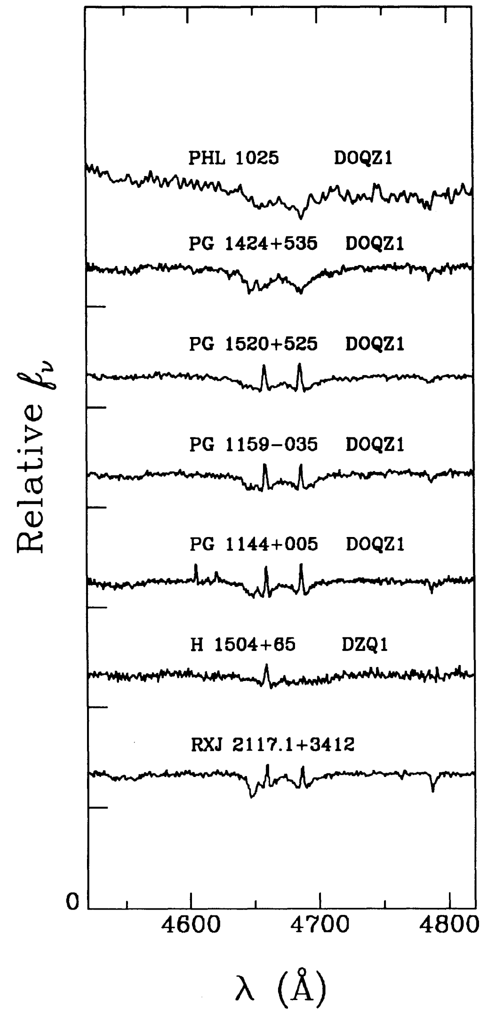


FIG. 16—Spectra of PG 1159 stars (Table 9) in the region 4520–4820 Å, which generally defines this class of hot, degenerate or predegenerate stars. The objects are grouped according to the classification scheme of Werner (1992). PHL 1025 and PG 1424+535 are in the **A** group of objects which display absorption features, while PG 1520+525, PG 1159 −035, PG 1144+005, and H 1504+65 are **E** objects with emission reversals (see text). Note the additional N V $\lambda\lambda$4604, 4620 emission in PG 1144+005. RXJ 2117.1+3412 is a member of the **lgE** group of low-gravity central stars which display narrower absorption wings.

11. THE MAGNETIC WHITE DWARFS

11.1 The Hydrogen-Atmosphere Stars

As mentioned in Sec. 2, the secondary type "P" describes magnetic white-dwarfs found to have polarized light, while "H" could be used instead if the star does not show significant polarization, but is found to be magnetic on the basis of the line spectrum.

The majority of magnetic white-dwarfs known today are hydrogen-line stars. They range in temperature from 5200 to 30,000 K, and their polar field strengths range from 3.5 MG to upward of 300 MG. Following Schmidt (1987), one can define three broad classes of such objects as a function of increasing field strength: for field strengths of a few MG only, the Balmer lines show a small and subtle splitting, such as that observed in the blue spectrum of the hot DA star PG 1658+441 (Fig. 18). The continuum does not show significant circular or linear polarization, although precise spectropolarimetry of the Balmer line profiles shows the signature of circular dichroism (Schmidt et al. 1992).

At moderately higher field values of the order of tens of MG, the Balmer lines split into a distinctive pattern of Zeeman components. For example, this is the case for Hα in LHS 1734 and G 99-47, two much cooler objects shown in Fig. 18. In the latter, a shifted, central π component was first reported by Liebert et al. (1975), and the σ components were later found in data with improved S/N ratio by Greenstein and McCarthy (1985). LHS 1734, discovered by Bergeron et al. (1992), has a temperature similar to that of G 99-47, but a weaker surface field. Similar splitting is seen in the 20,000 K magnetic DA star PG 1533−057, with polar field of 31 MG, which shows a fairly broad Hα complex, as well as somewhat sharper Hβ components. These stars generally show detectable continuum circular polarization at $\leqslant 1\%$, but not significant linear polarization. They may therefore be discovered as DAP stars using broadband polarimetry.

Finally, above 100 MG, the spectrum becomes completely distorted, to the point that recognizable Zeeman triplets of individual Balmer transitions are no longer seen, and identification of the underlying star as a DA star can be seriously hampered. This is the case of the famous magnetic white-dwarf Grw+70°8247, whose peculiar spectrum was first observed by Minkowski (1938), and which only recently has been unambiguously identified as a DA star

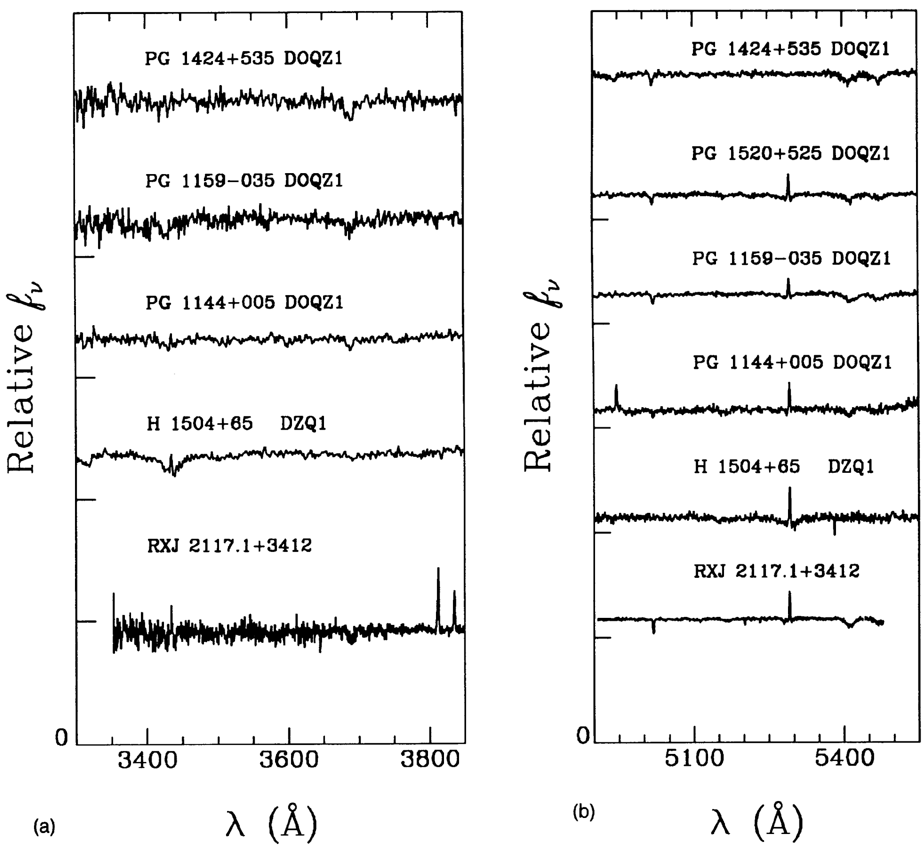


FIG. 17—(a) Same as Fig. 16, but for the 3300–3850 Å region, which contains O VI λ3435, C IV λ3689, O VI $\lambda\lambda$3811, 3834. (b) Same as Fig. 16, but for the 4900–5500 Å region, which contains the C IV $\lambda\lambda$5017, 5471, O VI λ5291, He II λ5411, and N V λ4945 lines. (c) Same as Fig. 16, but for the 5700–5900 Å region, which contains the C IV $\lambda\lambda$5801, 5812 doublet. (d) Same as Fig. 16, but for the 6400–6700 Å region, which contains the He II λ6560 line.

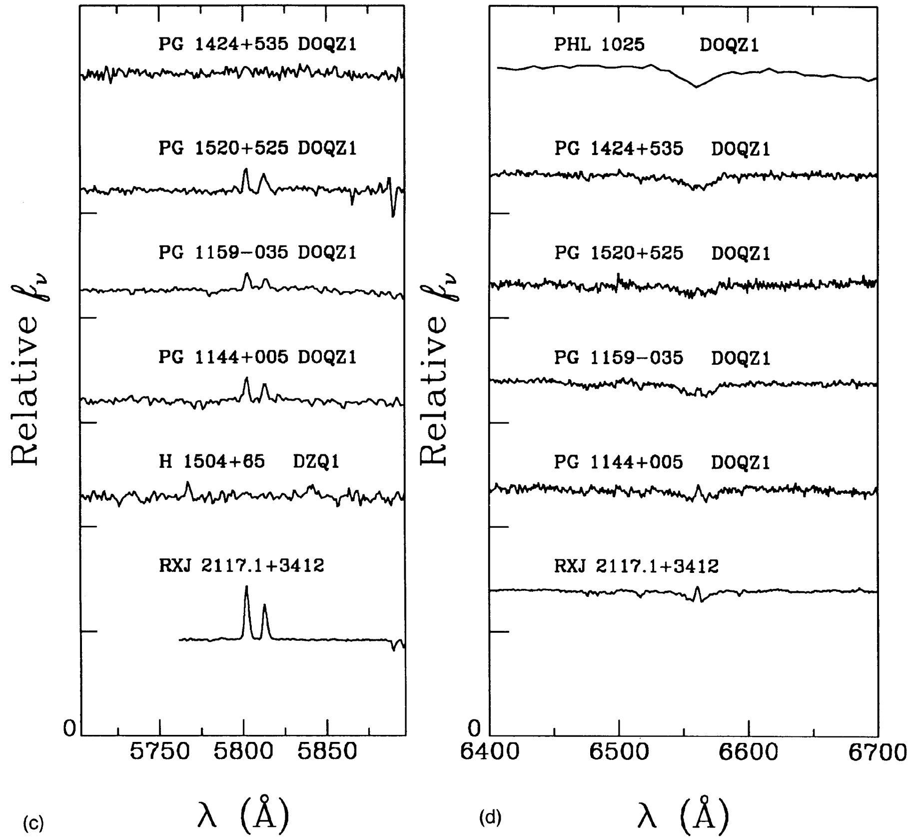


FIG. 17—(Continued)

with an estimated polar field of ~350 MG (Greenstein et al. 1985; Angel et al. 1985). These stars of highest field strengths generally show both linear and circular polarization as a strong function of wavelength, usually with amplitudes exceeding 1%.

TABLE 10
The Sample of Magnetic DA White Dwarfs

Name	Catalog Name	Sp. Type	Ref.
PG 1658+441	WD 1658+440	DAP2	*a*
LHS 1734	WD 0503−174	DAH9	*b*
G 99-47	WD 0553+053	DAP9	*c*
PG 1533-057	WD 1533−057	DAP3	*d*
Grw +70°8247	WD 1900+706	DAP4.5	*e*
GD 356	WD 1639+537	DAEH6.5	*f*

[a] $B_p \sim 3.5$MG; Liebert et al. (1983); Schmidt et al. (1992)

[b] $B_p \sim 6$MG; Bergeron, Ruiz, and Leggett (1992)

[c] $B_p \sim 25$MG; Liebert, Angel, and Landstreet (1975); Greenstein and McCarthy (1985)

[d] $B_p \sim 31$MG; Liebert et al. (1985)

[e] $B_p \sim 350$MG; Minkowski (1938); Greenstein and Matthews (1957); Greenstein, Henry, and O'Connell (1985); Angel, Liebert, and Stockman (1985); Greenstein and Liebert (1990); Jordan (1992)

[f] $B_p \sim 15$MG; Greenstein and McCarthy (1985)

For completeness, we have also included the spectrum of the peculiar moderate-field object GD 356, first analyzed by Greenstein and McCarthy (1985). Its spectrum is unique in that it is characterized by resolved Zeeman triplets of Hα and Hβ lines in *emission,* perhaps the sign of chromospheric activity in this unusual object.

TABLE 11
The Sample of Helium-Atmosphere and Unidentified Magnetic White Dwarfs

Name	Catalog Name	Sp. Type	Ref.
Feige 7	WD 0041−102	DBAP3	*a*
G 99-37	WD 0548−001	DQP8	*b*
G 227-35	WD 1829+548	DQP7.5	*c*
GD 229	WD 2010+311	DXP2	*d*
G 240-72	WD 1748+708	DXP11	*e*

[a] Liebert et al. (1977); Achilleos et al. (1992)

[b] Greenstein (1974)

[c] Greenstein (1970); Greenstein, Gunn, and Kristian (1971)

[d] Greenstein, Schmidt, and Searle (1974); Greenstein (1974); Liebert (1976); Wegner (1976); Greenstein and Boksenberg (1978)

[e] Greenstein (1974); Liebert (1976); Wegner (1976)

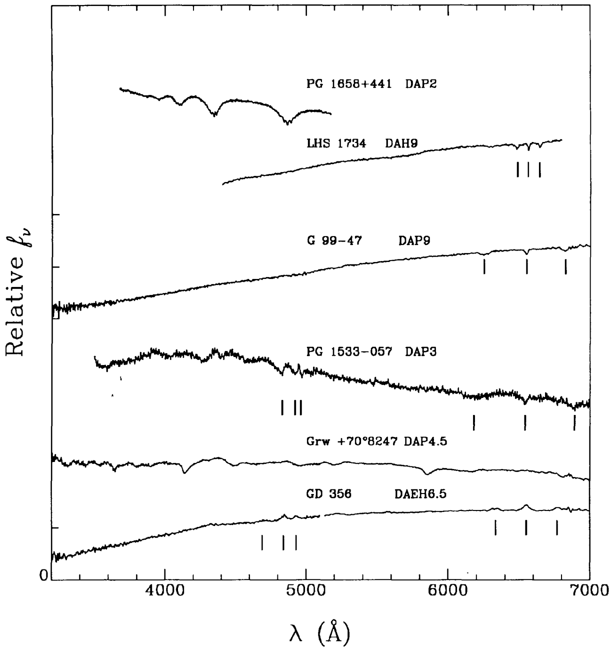


FIG. 18—Optical spectra of magnetic DA stars (Table 10), presented (except for GD 356) in order of increasing magnetic field strength. The weak-field ($B_p \sim 3.5$ MG) DAP2 star PG 1658+441 shows Zeeman splitting in the cores of Hβ and Hγ. The cooler stars LHS 1734 and G 99-47 show Hα in polar fields of 11 and 25 MG, respectively, while the 20,000 K star PG 1533-057 shows a rich Balmer line spectrum in a 31 MG polar field. The spectrum of Grw+70°8247 shows puzzling strong features near 4137 and 5855 Å, together with weaker ones near 3670, 3885, 4310, and 4488 Å. Its spectrum is that of a DA star in a 350 MG polar field. At the bottom, the unique DA star GD 356, which shows a resolved pattern of Zeeman components of Hα and Hβ *in emission.*

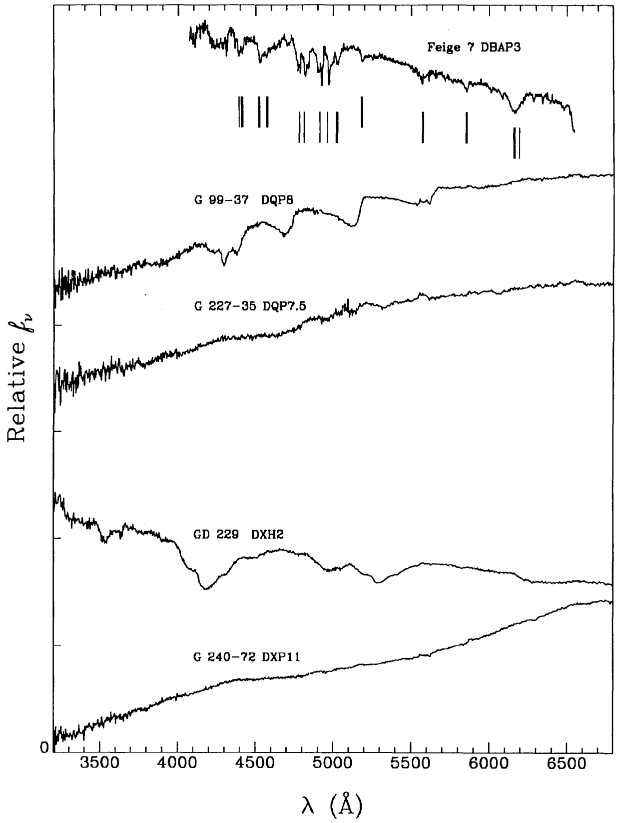


FIG. 19—Optical spectra of helium-atmosphere and unidentified magnetic white-dwarfs (Table 11). Feige 7 is a hot, helium-rich star with a rich spectrum of resolved Zeeman components of H I (thin tick marks) and He I (thick tick marks). G 99-37 and possibly G 227-35 show C_2 Swan bands, accompanied in the former with an unusual CH band near 4300 Å. The bottom two stars show still unidentified features: GD 229, with deep features near 4170 Å and 5250 Å together with weaker ones near 4800, 4950, and 6300 Å, and G 240-72, with a yellow sag in the 4400–6300 Å region.

11.2 The Helium-Atmosphere and Unidentified Magnetic Stars

This rather sparsely populated group of magnetic white-dwarfs is considerably less homogeneous than that of the magnetic DA stars, with each star exhibiting unique features. The DBAP3 star Feige 7, discovered by Liebert et al. (1977), is a 22,000 K, rotating star with a field near 20 MG; it shows a rich spectrum of well-resolved Zeeman components of both H I and He I, variable with the 2.2 h rotation period. Its atmosphere is helium dominated, but the distribution of elements at its surface is likely to be inhomogeneous (Achilleos et al. 1992). G 99-37, classified DQP8, is another unique, moderate field, object whose spectrum exhibits the C_2 Swan bands, characteristic of the DQ stars, together with the G band of CH, seen as a broad depression near 4300 Å in Fig. 19. Another broad depression, seen near 3900 Å, is attributed by Greenstein and Liebert (1990) either to CH or CN. The red spectrum shows no evidence for Hα. The third object in Fig. 19, the circularly polarized star G 227-35, originally classified DC by Hintzen and Strittmatter (1974), shows only a broad dip near 4550 Å, first reported by Greenstein (1974). It is now reclassified DQP by Greenstein and Liebert (1990). However, since it is highly polarized, this classification must be regarded as tentative.

Finally, two stars of unknown composition, whose spectra are both classified DXP: GD 229 is a ~16,000 K, strongly polarized star, whose spectrum is characterized by deep absorption features near 4170 and 5250 Å (Greenstein et al. 1974), as well as shallower depressions near 4800, 4950, and 6300 Å. G 240-72, on the other hand, is a cool, polarized magnetic star. Its spectrum, first described by Greenstein (1974), is characterized by a yellow sag—perhaps related to cyclotron absorption or to Zeeman splitting of Balmer lines in a complex field pattern (Arnaud et al. 1992)—in the 4400–6300 Å region. The existence of this broad absorption feature was later confirmed by Liebert (1976) and Wegner (1976). It is clearly visible in Fig. 19. Despite the report of possible additional weak features by Wegner (1976), no other features are clearly apparent, and the spectrum is otherwise that of a DC star.

12. CONCLUDING REMARKS

With this work, we have provided a complete and detailed atlas of optical spectra of white-dwarf stars for all the major types, as well as most—if not all—of the subtypes in use today. The inventory is rich, especially when compared with earlier attempts by Greenstein (1960), more than 30 years ago: the art of classifying white-dwarf spectra has blossomed far beyond the simple assignment of a DA or DB type. However, one should keep in mind that, beyond this sophisticated cataloging and classifying looms a much more ambitious aim: that of being able, someday, to understand the relationship that exists between white-dwarfs of different spectral types. If progress achieved in this specific area over the last 30 years is any indication, we should be approaching our goal of a full physical description of these dense atmospheres, which provide us with laboratories in which atoms and molecules radiate and absorb in conditions unattainable on Earth.

This project, in the works for an embarrassingly long number of years, *could not have been carried out* without the cooperation of many of our colleagues. Specifically, we would like to express our warmest thanks to the following people for contributing their published data to this effort, or for the interest they have expressed in this work: P. A. Aannestad, N. Achilleos, H. E. Bond, D. Daou, N. Dolez, M. S. Fulbright, U. Heber, J. B. Holberg, S. J. Kenyon, K. Kidder, J. Maza, C. Motch, E. P. Nelan, J. B. Oke, M. W. Pakull, M. T. Ruiz, R. A. Saffer, G. D. Schmidt, H. L. Shipman, E. M. Sion, P. Thejll, R. W. Tweedy, G. Vauclair, G. Wegner, K. Werner, D. T. Wickramasinghe, M. A. Wood, and F. H. Yackovich. Among those, S. J. Kenyon, G. Wegner, and K. Werner should be singled out for cheerfully, unselfishly, and tirelessly providing large quantities of essential data. E. M. Sion provided invaluable advice on spectral classification matters, while J.-S. Caux contributed significantly to the production of the final version of this atlas. This work ws supported in part by the NSERC Canada, by the Fund FCAR (Québec), and by NSF grant AST 89-18471.

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