THE ASTROPHYSICAL JOURNAL, 361:190–196, 1990 September 20

THREE UNRESOLVED DOUBLE DEGENERATE BINARIES

P. BERGERON,[1] JESSE L. GREENSTEIN,[2] AND JAMES LIEBERT[1]
Received 1990 January 29; accepted 1990 March 20

ABSTRACT

We present an atmospheric analysis of the DA white dwarfs G4–34, GD 402, and GD 387. The energy distributions and hydrogen line profiles of these stars are shown to be inconsistent with those obtained from single *or* double DA stars. Our result indicates that these stars are probably composite systems consisting of pairs of unresolved DA and DC stars, with the featureless component diluting the hydrogen line strengths of the DA white dwarf. An algorithm is developed to constrain the atmospheric parameters of the components of each system. Some possible implications of the existence of such DA + DC composite systems on the frequency of close, double degenerate binary systems are discussed.

Subject headings: stars: binaries — stars: stellar statistics — stars: white dwarfs

I. INTRODUCTION

The search for close, double degenerate binary systems has been a formidable task, for which progress has been understandably slow. While it is true that a handful of wide pairs of white dwarfs shown to have common proper motion are known (Greenstein 1986*a*), these have typical separations of order 10^2 or 10^3 AU, too wide for past or future phases of binary interaction. Until recently, no double degenerate binaries were known in which the components are close enough that the system had to have undergone at least one phase of common envelope evolution. The discovery that L870-2 (EG 11, WD 0135−052) is a double DA degenerate pair with a period of approximately 1.5 days (Saffer, Liebert, and Olszewski 1988; see also Greenstein 1983) shows that this kind of close binary really does exist, as required by hypotheses for the origins of hot subdwarfs or Type I supernovae (Webbink 1984; Iben and Tutukov 1987; Tutukov and Yungelson 1987).

However, L870-2 may be regarded as almost the ideal case for discovery as a double-lined spectroscopic binary. First, the white dwarfs are of comparable brightness, so that both sets of lines are visible. Second, the star is among the nearest known white dwarfs, and an accurate trigonometric parallax measurement could be invoked (Greenstein 1983) to show that it is considerably overluminous with respect to single white dwarfs of similar temperatures and known distances. Third, L870-2 is also one of the brightest white dwarfs at 12th mag, so that high-dispersion spectroscopy was possible with a reasonable amount of large telescope time. Fourth, both components are of DA spectral type and are cool enough that the Hα line has a sharp, non–LTE core, so that radial velocity measurements to the accuracy of several kilometers per second were possible.

The demonstration of the periodic velocity curve for this near-optimum case still required several nights of Multiple Mirror Telescope observations with a somewhat lucky scheduling. No effective survey of significant numbers of white dwarfs for similar periods has yet been published, although searches for larger velocity modulations indicative of smaller separations and shorter periods have thus far yielded null results (Robinson and Shafter 1987; Foss, Wade, and Green 1990). It is possible that the frequency of binary white dwarfs with periods longer than a few hours is in fact high. The great majority might easily be "difficult" cases with dissimilar luminosities, non–DA spectral types, high temperatures, no trigonometric parallaxes and/or separations wide enough that the velocity variations are small, but close enough for the combined image to be spatially unresolved.

Greenstein and Liebert (1990) have identified three white dwarfs (G4–34 = WD 0239+109; GD 402 = WD 2216+484; GD 387 = WD 2003+437) out of a sample of 75 DA stars having high signal-to-noise (S/N) ratio CCD spectrophotometry (Greenstein 1986*b*) in which study of the colors and hydrogen line profiles suggested that each might consist of an unresolved DA and DC star, with the featureless object being similar enough in temperature to the DA star to dilute substantially the hydrogen line strengths. Bergeron (1988) had already suggested that one of these candidates might be just such a spectroscopic binary, although not necessarily a close pair with detectable velocity variations. These would be the first such unresolved white dwarf pairs of dissimilar spectral type to be discovered. A few of the wide white dwarf pairs have dissimilar spectral type (Oswalt *et al.* 1988), and a handful of unresolved white dwarf–main-sequence binaries are known (Greenstein 1986*a*).

This paper presents a detailed analysis of the line profiles and spectrophotometry for each object. Detailed models are used to demonstrate that composite DA + DC systems must be considered in order to reproduce the observed spectra. The atmospheric parameters for each stellar component are determined as far as possible. The approach is somewhat similar though generally coarser than the analysis of L870-2 by Bergeron *et al.* (1989). The deconvolutions for each stellar component of the three binaries are presented in § II. The astrophysical implications of the existence of these systems are then discussed in § III.

II. DECONVOLUTION AND FITTING TECHNIQUES

High signal-to-noise ratio (S/N ~ 150) spectra of G4–34, GD 402, and GD 387 have been obtained by Greenstein (1986*b*) using the double CCD spectrograph attached to the Hale 5 m reflector of the Palomar observatory. The blue spectrum (~3300–5200 Å) and red spectrum (~5200–9500 Å) of each star have been combined to obtain a more complete energy distribution. Because of technical problems with the blue-sensitive CCD, only a single spectrum of GD 402 was

[1] Steward Observatory, University of Arizona.
[2] Palomar Observatory, California Institute of Technology.

obtained covering the 4200–8800 Å range. We compared preexisting multichannel spectrophotometry (Greenstein 1984 and unpublished fluxes) with this CCD data set and found good agreement for the observed energy distributions of G4–34 and GD 387 (but not GD 402). The CCD spectra are displayed in Figure 2. Irregularities at 5577 Å in some spectra arise from bad night sky subtraction. Discontinuities are also found near 5200 Å due to the presence of the dichroic filter used in the double CCD camera. Further details on the data acquisition can be found in Greenstein (1986*b*).

The line profiles and energy distributions have been analyzed with new model atmospheres and synthetic spectra appropriate to the study of cool DA white dwarfs (Bergeron, Wesemael, and Fontaine 1990; Bergeron *et al.* 1990*a*, *b*), and also ZZ Ceti stars (Daou *et al.* 1990). The model atmospheres are in LTE, are hydrogen-line–blanketed, and have mixed hydrogen and helium compositions. They also take into account the energy transport by convection. The thermodynamical stratifications of these models are used to calculate detailed synthetic spectra of the Balmer lines and also broader energy distributions. The population of the individual levels of the hydrogen atom is calculated within the occupation probability formalism of Hummer and Mihalas (1988). This formalism provides the theoretical framework to treat accurately how the different high-lying levels of the hydrogen atom are perturbed by surrounding particles and also allows a detailed analysis of the gravity-sensitive (and helium-sensitive) high Balmer lines.

The first step in our analysis consists in fitting the hydrogen line profiles and energy distributions with the assumption that each star is a single DA white dwarf. The fits to the Balmer line profiles are obtained with the same technique used by Bergeron *et al.* (1990*b*) and Daou *et al.* (1990) where the flux of each line is first normalized, in both observed and model spectra, to a continuum set at a fixed distance from the line center. In a second step, the temperature-sensitive lines Hγ and Hδ (or lower lines when Hγ and Hδ are not available) are used to determine the effective temperature at a given surface gravity. The procedure is then repeated with different values of the surface gravity until the profile of the gravity-sensitive lines, Hϵ and H8, are well reproduced. Because our study represents only an exploratory calculation, we limit ourselves to values of $\log g = 7.5$, 8.0, and 8.5. We first assume a pure hydrogen atmospheric composition for the DA models.

Although this last assumption is probably well justified for hot ($T_e > 12{,}000$ K) DA stars, Bergeron *et al.* (1990*a*) have shown that the atmospheres of most DA white dwarfs below $T_e = 12{,}000$ K are contaminated by large amounts of helium, sometimes as high as $N(\mathrm{He})/N(\mathrm{H}) \sim 20$. The presence of helium in the atmospheres of cool DA stars has the effect of increasing the atmospheric pressure and thus affects the way high-lying levels of the hydrogen atom are perturbed. Furthermore, it has been shown that the pressure effects originating from increased helium abundance *or* from an increased surface gravity cannot be separated (Bergeron, Wesemael, and Fontaine 1990). When composite spectra are considered, however, the helium-abundance and surface-gravity effects are no longer equivalent because the total luminosity of the system is weighted by the radius of each component, which is dependent only on the value of the surface gravity. But again, since it is not possible in the following analysis to constrain in detail all the atmospheric parameters [T_e, $\log g$, and $N(\mathrm{He})/N(\mathrm{H})$], we will explore only briefly the effect of varying the atmospheric composition.

Finally, the fits to the energy distributions are obtained by first reducing the observed CCD spectrophotometry to several narrow-band normal points; the effective temperature is then obtained with least-squares fitting techniques, provided that both the models and the observed spectra are normalized at the same wavelength. We discuss in turn the results of our analysis for each individual object.

a) G4-34

Figure 1*a* displays our best fit to the Balmer lines of G4–34 assuming a single DA star. Although the fit to the higher Balmer lines (Hδ–H8) is marginally acceptable, the profiles of the lower lines (Hα–Hγ) are clearly not well reproduced. This represents our best fit, but it is certainly not an acceptable fit. This discrepancy is further emphasized when the energy distribution of G4–34 is fitted with single DA models. Our result, presented in Figure 2*a*, shows that the effective temperature obtained from the energy distribution ($T_e = 8130$ K) is at odds with that obtained from the trial spectroscopic fit ($T_e = 7260$ K). No self-consistent fit to both the energy distribution and the Balmer line profiles could be achieved with a single DA white dwarf model for any T_e and $\log g$ [or $N(\mathrm{He})/N(\mathrm{H})$] values. We have thus explored a different avenue by assuming that G4–34 is instead an unresolved binary system composed of two white dwarfs, of which at least one component needs to be a DA star in order to produce the observed hydrogen lines.

The analysis of the close detached binary DA white dwarf L870-2 by Bergeron *et al.* (1989) is an example of such a calculation where composite synthetic spectra of DA white dwarfs are used to constrain the atmospheric parameters of each component of the system. Although their conclusion was restricted to a narrow range of atmospheric parameters, a more complete analysis reveals that the *line profiles obtained from the sum of two DA spectra at different effective temperatures and surface gravities can always be fitted by a single DA star at an intermediate temperature and surface gravity.* As can be seen from Figure 1*a*, the line profiles of G4–34 cannot be fitted by a single DA spectrum. This indicates that no better fit can be obtained by using a composite DA spectrum to fit the data. We have therefore considered the possibility that the system be composed of a DA star and a non–DA star (in this case a featureless DC white dwarf).

Our first step is to assume surface gravities for both the DA and the DC components. We then start with a given effective temperature for the DC component, T_e(DC), and find the temperature of the DA component, T_e(DA), which best fits the profile of the Balmer lines. This is accomplished by adding the surface fluxes from both components (weighted by the respective radii obtained from the evolutionary sequence of Wood [1989] for a carbon core composition), and by using the same line-profile fitting technique as described above. For that value of T_e(DC), the *best* fit does not necessarily represent a *good* fit to the data. The effective temperature of the DC component is then varied, and the best T_e(DA) is again found; in this manner, a set of optimal T_e(DC)–T_e(DA) pairs is defined. This set of effective-temperature pairs is then used to calculate composite energy distributions. The observed energy distribution is finally used to constrain the best value of T_e(DC)–T_e(DA). The whole procedure is then repeated with different surface gravities until a self-consistent solution is found for both the line profiles and the energy distribution.

For G4–34, the best fit was achieved with a DA component at $T_e = 9620$ K, $\log g = 8.5$ and a DC component at $T_e = 7660$ K, $\log g = 7.5$. The resulting fits are displayed in Figures 3*a*

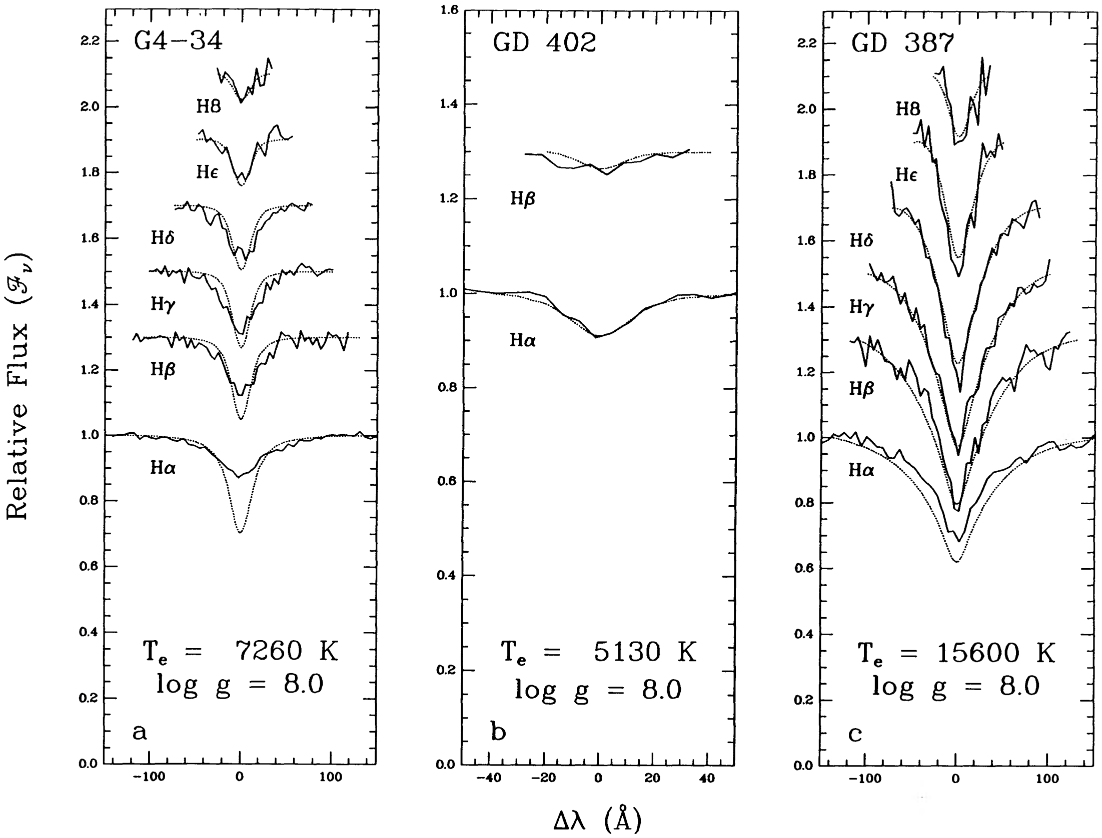

FIG. 1.—Our best fit to the line spectrum of G4–34, GD 402, and GD 387 obtained under the assumption that a single DA star is being fitted. The continuum of each line has been normalized to unity, and the higher lines have been shifted vertically from each other, for separation in plotting (the separation is 0.3 between Hα and Hβ, and 0.2 between every other lines).

and 4*a*. The important physical aspect in our solution is the dilution of the line profiles of the DA white dwarf by the DC component. The line-profile analysis shows that the DC component must have a lower surface gravity (and thus a larger radius and higher luminosity) than the DA component to ensure that the dilution of the DA line profiles is large enough. For example, when the difference in surface gravity of both components is reduced to only 0.5 dex, with similar effective temperatures, the Hα line profile is always predicted to be deeper than observed. Although the atmospheric parameters of both components cannot be determined with great accuracy, it may be concluded, however, that the DA is the hotter of the two stars, the DC has the lower surface gravity (higher luminosity), and the effective temperature of each component is in the range 7500–9700 K.

The analysis of Bergeron *et al.* (1990*a*) showed that a DA star with an effective temperature near $\sim$9500 K should have a helium-enriched atmospheric composition. Therefore, we have explored the possibility that the DA component of the G4–34 system also has a helium-rich composition. With the assumption that the DA component has $N(\mathrm{He})/N(\mathrm{H}) \sim 1$, we could reach an acceptable solution by reducing by $\sim$200 K the effective temperature of the DC component, and by further increasing by 0.2 dex the difference in surface gravity between both components of the system. If G4–34 is the result of binary evolution, however, it is not clear if the DA component of the system has followed the same evolutionary path as other single DA white dwarfs and mixed its thin hydrogen layer.

b) GD 402

GD 402 is a cool spectroscopic DA white dwarf which was first suspected by Bergeron (1988) to be a composite system. In this case, the spectroscopic temperature obtained from a fit to the profile of Hα and Hβ was found some $\sim$1500 K cooler than the temperature obtained from photometric color indices. We go one step further here by making use of the full energy distribution of GD 402 to constrain the atmospheric parameters of both components of the system.

Figures 1*b* and 2*b* show the best fit to GD 402 using single DA white dwarf models. Because of the absence of the high Balmer lines, we have little sensitivity to the surface gravity, and the adopted value of log $g = 8.0$ should be considered uncertain. Our analysis basically confirms the result of Bergeron (1988) that the spectroscopic temperature is significantly cooler than that obtained from the energy distribution, and thus that GD 402 is probably a composite system. In this particular case, even if the observed line profiles can be fitted by a single DA spectrum, the system cannot be composed of two DA white dwarfs. Indeed, in order for the energy distribution to be hotter, a hot DA white dwarf has to be considered in the system and would thus produce many high Balmer lines which are not observed. Therefore, the hot component of the system has to be a DC white dwarf.

We have thus repeated the above procedure and found a best fit to the line spectrum and the energy distribution with a DA component at $T_e = 6200$ K, log $g = 8.0$, and a DC com-

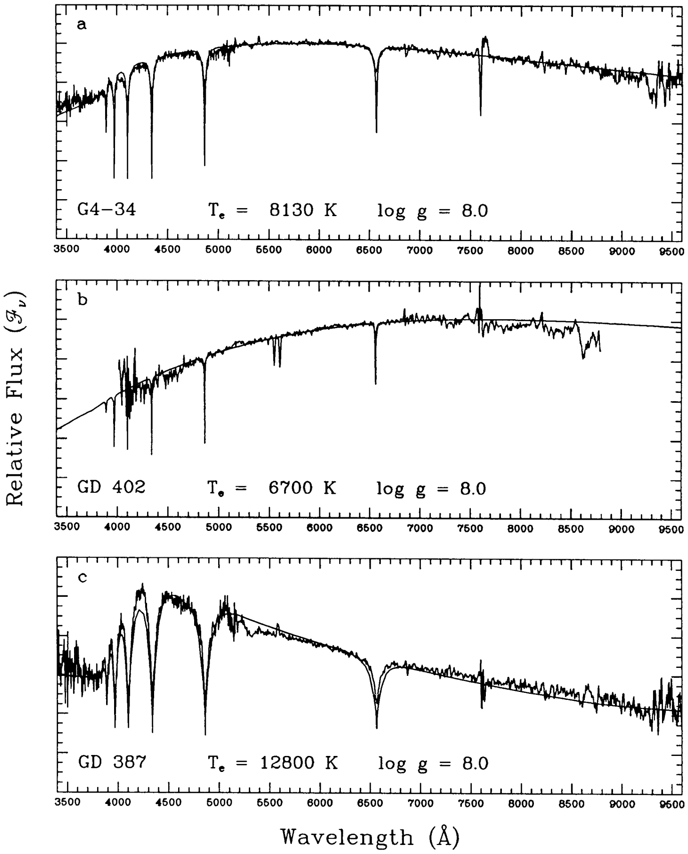

FIG. 2.—Our best fit to the energy distribution of G4–34, GD 402, and GD 387 obtained under the assumption that a single DA star is being fitted. The energy distributions have been normalized at 5500 Å (G4–34), 6950 Å (GD 402), and 4500 Å (GD 387).

ponent at $T_e = 7080$ K, log $g = 8.0$. At this low temperature, the DA component is expected to have an almost pure hydrogen composition (Bergeron *et al.* 1990*a*). The resulting fits are presented in Figures 3*b* and 4*b*. Again, because of the absence of the gravity-sensitive high Balmer lines, the surface gravity of each component cannot be accurately determined. A measure of the parallax would help to improve our determination of the surface gravity of both components.

c) GD 387

This third case is a much hotter star in which Greenstein and Liebert (1990) had noticed that the observed Hα line was substantially weaker than predicted from single DA models. Our best fit to the Balmer lines is presented in Figure 1*c*. A better fit to the higher Balmer lines could be obtained by slightly reducing the surface gravity. The energy distribution fit (Fig. 2*c*) yields a much lower effective temperature ($T_e = 12{,}800$ K) than the spectroscopic fit ($T_e = 15{,}600$ K), again assuming a single DA star.

We encountered greater difficulty in reaching a self-consistent solution for this object assuming a composite DA + DC spectrum. The best solution from the observed line profiles is achieved when both stars have log $g = 7.5$ and effective temperatures of 13,000 K and 7500 K for the DA and DC components, respectively. However, in order to fit the energy distribution, a much better fit is obtained when the DC component is considerably cooler. Our adopted solution is a DA component at $T_e = 14{,}340$ K, log $g = 7.5$, with a DC component at $T_e = 6000$ K, log $g = 7.5$. The resulting fit to the line profiles is displayed in Figure 3*c* and indicates that the Hα line profile is still predicted to be too weak. Fine adjustments of the surface gravity of each object may improve the solution. The energy distribution of our adopted solution (Fig. 4*c*) is definitely a large improvement over the solution obtained with single DA models (Fig. 2*c*). This system would be far better understood if a parallax were available. The energy distribution especially at $\lambda > 8000$ Å might directly reveal the cool DC.

Despite these uncertainties, the main conclusion for this composite object is that the DA is the hotter component at $T_e = 13{,}000$–$16{,}000$ K, and the companion is a cool DC which may fall in a range of effective temperature of 6000–7500 K. Also, the surface gravities of both stars are probably very low.

III. SOME IMPLICATIONS

With the solutions obtained above for the three systems, we have calculated bolometric corrections and absolute visual magnitudes for each component following Wesemael *et al.* (1980). We have also estimated the composite absolute visual magnitudes and the expected parallaxes for each system by using the V magnitudes quoted in McCook and Sion (1987). The maximum physical separations on the plane of the sky allowed by these distances within a seeing diameter of 2″ were also calculated. The derived parameters for each system are summarized in Table 1. Accurate trigonometric parallax measurements could confirm our results by showing whether each object is overluminous in comparison with other DA white dwarfs of similar colors (see below). Were we to interpret these systems as each containing only a DA star of temperature and gravity given in Table 1, the predicted parallaxes would have been G4–34, 0″025; GD 402, 0″035; GD 387, 0″0073. In the composite systems G4–34 and GD 402, where components of similar temperature make comparable contributions at optical wavelengths, the predicted differences in parallaxes are large, well within the capability of modern parallax observers. In GD

TABLE 1

ATMOSPHERIC PARAMETERS AND PREDICTED PARALLAX OF THE THREE COMPOSITE SYSTEMS

	DA COMPONENT			DC COMPONENT			COMPOSITE SYSTEM		
STAR	T_e (K)	log g	M_V	T_e (K)	log g	M_V	M_V	Predicted Parallax	Maximum Separation (AU)[a]
G4–34	9620	8.5	13.20	7660	7.5	12.53	12.06	0″015	130
GD 402	6200	8.0	14.07	7080	8.0	13.42	12.94	0.021	95
GD 387	14340	7.5	10.75	6000	7.5	13.54	10.67	0.007	280

[a] Assuming a 2″ angular separation between both components.

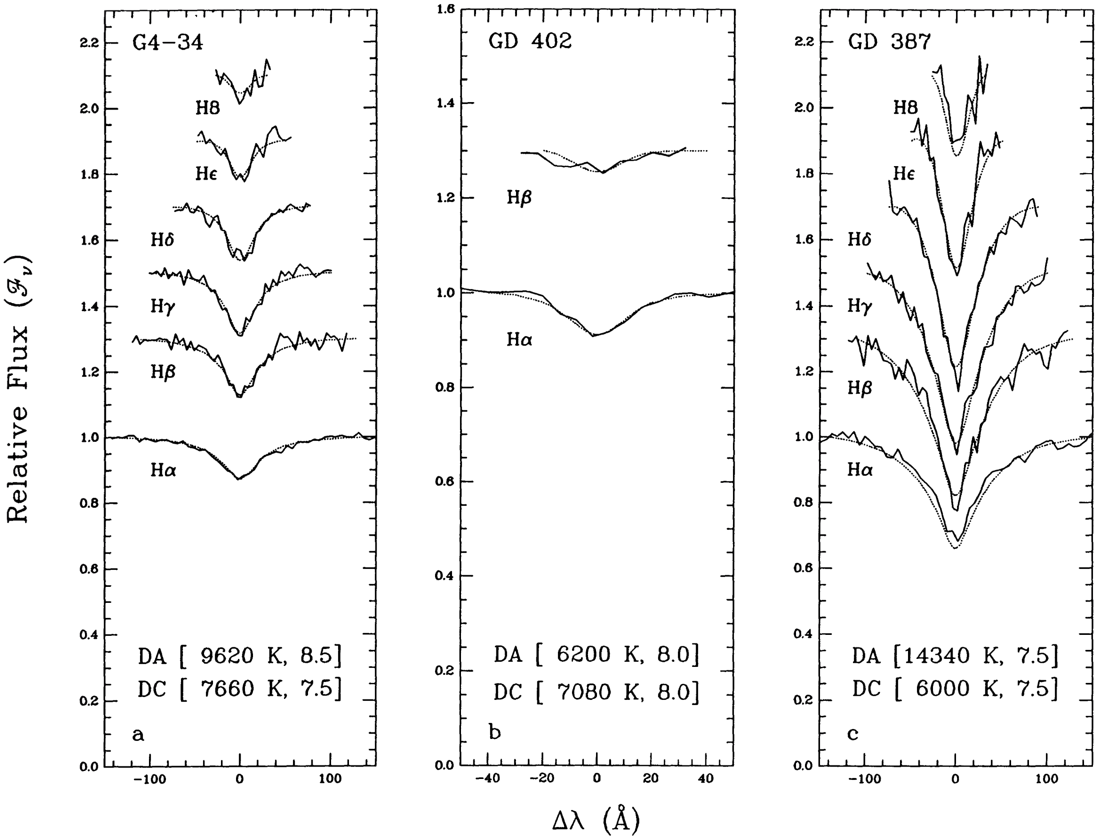

FIG. 3.—Our best fit to the line spectrum of G4–34, GD 402, and GD 387 obtained under the assumption that a composite DA + DC system is being fitted. The continuum near each line has been normalized to unity, and the higher lines have been shifted vertically from each other as in Fig. 1.

387, detection of the red DC companion by either parallax or photometry appears difficult, and its predicted parallax is small.

A composite DA + DC system having components with dissimilar temperatures might be detectable in other parts of the observed energy distribution. Is the 6000 K DC component in GD 387 detectable in the red or near infrared? The Greenstein (1984) multichannel spectrophotometry showed that composites containing a main-sequence dM star are easily recognized by their DEL$(V-I) = (V-I) - 0.88(G-R)$, a quantity measuring the nonlinearity of a spectrum. Unfortunately, our hypothetical cool DC contributes far less red light than a dM star. The DEL$(V-I)$ from either the double spectrograph or the multichannel photometry is -0.04 mag for GD 387, at the lower boundary of normal single DA white dwarfs (see Fig. 2 of Greenstein 1984). GD 387 has the same DEL$(V-I)$ as does HZ 43 (WD 1314+294), a hot DA star with a close dM companion whose scattered light affects the photometry. In contrast, the similarity in temperatures of each component in the G4–34 and GD 402 system suggests that colorimetric detection of their companions is impossible.

The distortion in the composite energy distribution of GD 387 may be larger at colors other than those cited above. Let us approximate the two white dwarfs by blackbodies of the same log g (i.e. radius) and compute color indices between various wavelengths. The composite system is brighter than the DA component alone by only -0.02 mag at $\lambda3570$, by -0.07 mag at $\lambda5405$, and by -0.28 mag at $\lambda22000$. Roughly, the colors of the composite system are about 10% different from those of the DA component (14,340 K) to those of the DC component (6000 K). DEL$(V-I)$ proves identical (-0.14 mag), while the $(J-H)$ and $(H-K)$ differ by -0.04 mag and -0.07 mag, respectively, an essentially undetectable amount in view of the scatter in the infrared color-color diagram of white dwarfs. The composite system has $(V-K) = -1.94$ mag while the DA component has $(V-K) = -2.15$ mag. In an ideal M_{5405}, $(V-K)$ diagram of great precision which would require new, accurate (and small) parallaxes, the composite would be above and to the right of the white-dwarf sequence. In the absence of such a parallax, comparison of precise optical–infrared energy distributions with the predictions of model atmospheres for single stars might show the modest excess at long wavelengths due to the cool companion. In any case, a purely photometric detection of the red DC companion in GD 387 appears very difficult.

Nonetheless, GD 387 has parameters well suited for recognition by comparison of the hydrogen line parameters with color (Greenstein and Liebert 1990). The most favorable situation for detectability of a companion to a DA on the basis of the dilution of the line strengths occurs near the maximum of the $W(\mathrm{H}\alpha)$, T_e curve (about 12,000 K), since for hotter and cooler stars the line profiles are much more sensitive to T_e and conclusions depend on the accuracy of the color measurements. We estimate that with high signal-to-noise ratio, we would recognize the existence of a cooler companion to a 12,000 K star if it were hotter than 7000 K, i.e., brighter than $0.12 \times L(\mathrm{DA})$. Such a yellow degenerate is common among the field population, and cases with much cooler companions like GD 387 may be relatively frequent. Unfortunately, undetectable companions cooler than 7000 K—which populate the peak of the lumin-

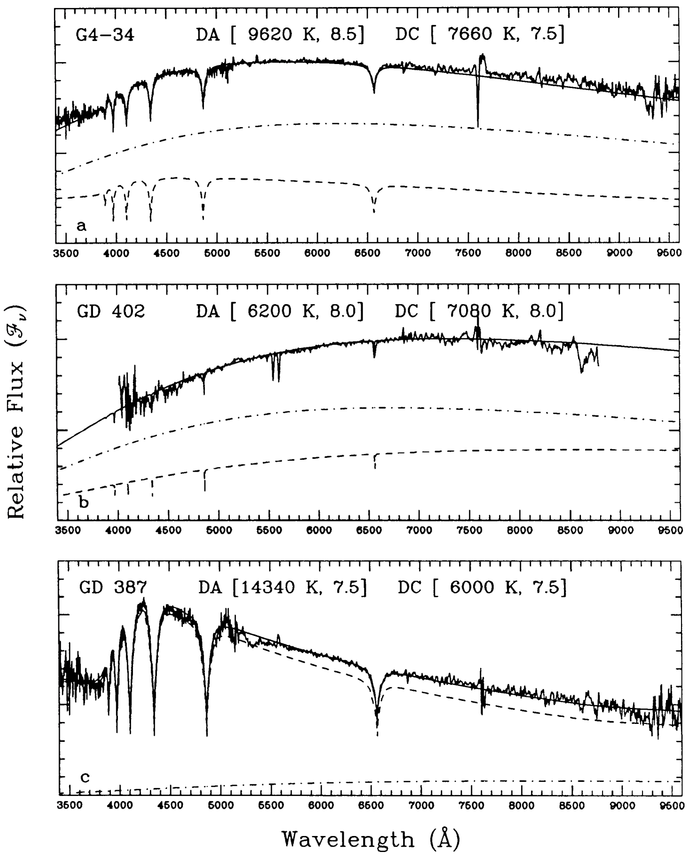

FIG. 4.—Our best fit to the energy distribution of G4–34, GD 402, and GD 387 obtained under the assumption that a composite DA + DC system is being fitted. The energy distributions have been normalized at 5500 Å (G4–34), 6950 Å (GD 402), and 5800 Å (GD 387). The individual contributions of the DA components (*dashed lines*) and the DC components (*dash-dotted lines*) have also been displayed.

osity function for field white dwarfs—might be even more common. Moreover, as discussed above, unresolved binary systems composed of two DA (or non–DA) stars are not detectable from analysis of the line profiles, nor are they easily recognized from the modest distortion of the energy distribution in comparison with that of single stars. Unless an accurate trigonometric parallax is known and the components have similar T_e—in which case the system could appear overluminous in an H-R diagram—those systems may remain undetected.

It is clearly difficult to obtain reliable statistics on what fraction of white dwarfs have fainter, unresolved degenerate companions. That the three cases studied here from the Greenstein (1986*b*) sample are double degenerate binaries seems highly probable. In Greenstein and Liebert (1990), four other DA's were mentioned which deviated by lesser amounts than G4–34, GD 387, and GD 402 from the normal relation between color and Hα line profile. These would be worth study with better data. If we consider only the DA + DC systems analyzed here or suspected by Greenstein and Liebert (1990), the fraction of the sample suspected to be unresolved double degenerates with dissimilar spectral types is between 4% and 10%. The true fraction could be much higher if many systems exist with similar spectral types or which have cool secondary stars.

An upper bound on the fraction of unresolved double degenerates may be inferred—at least in principle—by considering what is known about the fractions of both very close and much wider pairs. The former is of greatest importance in determining the frequency of systems which may evolve into novae or supernovae. For such binaries, systematic radial velocity monitoring will suffice. The radial velocity surveys (Robinson and Shafter 1987; Foss, Wade, and Green 1990) suggest that very close white dwarf pairs with separations of the order of 0.01 AU account for at most several per cent of the space density of field white dwarfs. Moreover, resolved double degenerates—typically with separations of the order 10–1000 AU—account for only about 1% of known white dwarfs (Greenstein 1986*a*). The even closer, currently interacting degenerate pairs which do exist are very rare and easily recognizable spectroscopically (e.g., AM CVn, G61–29). It does not seem likely that the spatially unresolved systems, whose likely physical separations overlap those of the velocity variable and common proper motion pairs, have a much higher frequency than either group.

In this study, nonetheless, all three companions are DC and it is even possible that this is *not* a selection effect! Does this suggest that interaction and mass exchange may have altered the atmospheric composition? Dimmer companions normally have been degenerate a longer time and are further down the cooling curve; since their main-sequence progenitors were more massive, the white dwarfs are likely to be more massive, fainter, and (for most of the cooling evolution) slower to evolve. The difference in luminosity between components decreases as they age; this "focusing" effect makes members of a noninteracting pair more alike. This favors detection by their being up to 0.75 mag overluminous in an H-R diagram, rather than by purely spectroscopic means. We might thus expect overluminous pairs to be most prevalent at the cool end of the sequence; a barely resolved example is that of the double DC system G107–70 (Harrington, Christy, and Strand 1981). Otherwise, except for the upper limit listed in the last column of Table 1, we have no inkling as to the range of physical separation of our doubles. Perhaps high-resolution imaging (or interferometric) techniques can be used, since the stars differ little in magnitude (except for GD 387). At a typical distance of 60 pc, 1″ is 60 AU; such a pair is noninteracting, the binary possibly visually resolvable. At 10 mas (not beyond the limits of interferometry), however, a pair with current separation of 120 $R_\odot$ may have been subject to interactions during red giant evolution. Further, radial velocity variations will be marginally detectable. For closer pairs, as previously noted, radial velocity measurements are the only means of obtaining direct information on the separation.

This work was supported in part by the NSF grant AST 88-18069. P. B. acknowledges support from a NSERC postdoctoral fellowship.

REFERENCES

Bergeron, P. 1988, Ph.D. thesis, Université de Montréal.
Bergeron, P., Wesemael, F., and Fontaine, G. 1990, *Ap. J.*, submitted.
Bergeron, P., Wesemael, F., Fontaine, G., and Liebert, J. 1990*a*, *Ap. J.* (*Letters*), **351**, L21.
Bergeron, P., Wesemael, F., Fontaine, G., Liebert, J., and Lacombe, P. 1990*b*, in preparation.
Bergeron, P., Wesemael, F., Liebert, J., and Fontaine, G. 1989, *Ap. J.* (*Letters*), **345**, L91.

Daou, D., Wesemael, F., Bergeron, P., Fontaine, G., and Holberg, J. B. 1990, *Ap. J.*, in press.
Foss, D., Wade, R., and Green, R. 1990, in preparation.
Greenstein, J. L. 1983, *M.N.R.A.S.*, **203**, 1213.
———. 1984, *Ap. J.*, **276**, 602.
———. 1986*a*, *A.J.*, **92**, 867.
———. 1986*b*, *Ap. J.*, **304**, 334.
Greenstein, J. L., and Liebert, J. 1990, *Ap. J.*, **360**, 662.
Harrington, R. S., Christy, J. W., and Strand, K. Aa. 1981, *A.J.*, **86**, 909.
Hummer, D. G., and Mihalas, D. 1988, *Ap. J.*, **331**, 794.
Iben, I., and Tutukov, A. V. 1987, *Ap. J.*, **313**, 727.
McCook, G. P., and Sion, E. M. 1987, *Ap. J. Suppl.*, **65**, 603.
Oswalt, T. D., Hintzen, P. M., Liebert, J., and Sion, E. M. 1988, *Ap. J.* (*Letters*), **333**, L87.
Robinson, E. L., and Shafter, A. W. 1987, *Ap. J.*, **332**, 296.
Saffer, R. A., Liebert, J., and Olszewski, E. M. 1988, *Ap. J.*, **334**, 947.
Tutukov, A. V., and Yungelson, L. R. 1987, in *IAU Colloquium 95*, *The Second Conference on Faint Blue Stars*, ed. A. G. D. Philip, D. S. Hayes, and J. Liebert (Schenectady: L. Davis), p. 435.
Webbink, R. F. 1984, *Ap. J.*, **277**, 355.
Wesemael, F., Auer, L. H., Van Horn, H. M., and Savedoff, M. P. 1980, *Ap. J. Suppl.*, **43**, 159.
Wood, M. A. 1989, private communication.

P. Bergeron and J. Liebert: Steward Observatory, University of Arizona, Tucson, AZ 85721

J. L. Greenstein: Palomar Observatory, California Institute of Technology, Pasadena, CA 91125