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THE ISOLATED MASSIVE DA WHITE DWARF GD 50

P. BERGERON,[1] K. M. KIDDER,[2,3] J. B. HOLBERG,[2,4] JAMES LIEBERT,[1] F. WESEMAEL,[4,5] AND REX A. SAFFER[1]

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ABSTRACT

Analysis of accurate hydrogen line profiles from optical and ultraviolet spectrophotometry shows that the hot DA white dwarf GD 50 (WD 0346−011) has an exceptionally high surface gravity of log $g = 9.0 \pm 0.15$; the derived parameters imply a mass of 1.2 $M_\odot$ and a radius of 0.0057 $R_\odot$, if an interior composed of carbon and oxygen is assumed. As such, it is the first well-studied, isolated DA white dwarf with a likely mass larger than that of Sirius B. Moreover, the derived mass is large enough to consider the possibility that the interior is composed of oxygen, neon, and magnesium. If GD 50 has evolved as a single object, it should be quite young. Alternatively, the star could have formed as the result of a merger of a close pair of white dwarfs.

Subject headings: stars: individual (GD 50) — stars: interiors — stars: white dwarfs — ultraviolet: spectra

1. INTRODUCTION

It is now well-established that the overwhelming majority of white dwarfs that are not members of close binary systems have masses far below the Chandrasekhar limit (Koester, Schulz, & Weidemann 1979; Wegner 1979; Shipman & Sass 1980; Weidemann & Koester 1984; McMahan 1989; Bergeron, Saffer, & Liebert 1991a, b). A mean mass near 0.6 $M_\odot$ has been found from these analyses of large samples especially of DA white dwarfs, primarily from a comparison of photometric and spectroscopic data with the predictions of model atmospheres. At the same time, the discovery and analysis of white dwarfs in young, open clusters implies that at least some main-sequence stars with initial masses as high as perhaps 8 $M_\odot$ evolve into white dwarfs (Romanishin & Angel 1980; Anthony-Twarog 1982; and especially Reimers & Koester 1988, and references therein). As expected from studies of asymptotic giant branch sequences in Magellanic Cloud clusters (Aaronson & Mould 1985), there is also evidence that the final remnant mass correlates positively with the initial mass, so that stars with very high initial masses end up with high final masses; the best-studied example of the latter is Sirius B, one of the few white dwarfs with an astrometric mass determination (1.05 $M_\odot$; Gatewood & Gatewood 1978).

The core composition of a truly massive white dwarf is also a subject of interest. Stellar evolution theory predicts that post–helium-burning stars with cores reaching masses of $\sim 1.2\ M_\odot$ should also reach temperatures sufficient to ignite carbon burning, near 8×10^8 K. This is predicted to occur for initial masses generally in the range 8–10 $M_\odot$ (Nomoto 1984), although these values may be modified by the inclusion of overshooting (Maeder & Meynet 1989). It is not clear that this burning cycle should occur in a nonviolet manner, so as to leave a white dwarf remnant whose core is composed of the products of carbon burning—oxygen, neon, and magnesium (ONeMg). However, the discovery of greatly enhanced abundances of O, Ne, and Mg in some novae ejecta (Truran & Livio 1986) seems to demonstrate that ONeMg white dwarf cores can be an outcome of the evolution of such a star in a close binary system. Hence, it would be very interesting if one could demonstrate such a case among single white dwarfs.

Since the final mass is expected to remain close to the average for initial masses up to several solar masses (Weidemann & Koester 1983), it is expected that only a small fraction of field white dwarfs should have masses exceeding 1 $M_\odot$, and it has been very difficult to identify unambiguously such cases for further study. Besides the expected rarity of such examples in a random sample of single degenerates, the method of fitting observed colors is limited by the accuracy of the data and confined to a limited range of effective temperatures for DA stars at which the amplitude of the Balmer jump is strongest and most sensitive to the surface gravity. For cool DA stars, there is the additional complication that any convective mixing of helium into the atmosphere will produce an increase in atmospheric pressure similar to that caused by increased surface gravity (Bergeron, Wesemael, & Fontaine 1991c). Several well-observed DA stars have been found to have masses moderately higher than the mean of 0.6 $M_\odot$—for example, a few in the Hyades cluster (Werner, Reid, & McMahan 1989) and one star in the Pleiades. Several white dwarfs found in young Galactic clusters have derived masses near or above 1 $M_\odot$, the best examples being associated with NGC 2516 (Reimers & Koester 1982). However, these parameters have necessarily large associated errors as the stars are quite distant and faint. No well-studied case of an isolated nonmagnetic DA star has a mass demonstrably exceeding that of Sirius B at 1.05 $M_\odot$.

For non–DA stars with helium-dominated atmospheres, the uncertainties in the physics are generally considered to be greater than for DA stars. Although the mean gravity of a sample of DB stars was not found to differ significantly from that for DA stars (Oke, Weidemann, & Koester 1984), we are aware of no well-studied DB star believed to have an abnormally large gravity and mass. However, Thejll et al. (1990) analyze the peculiar white dwarf G35−26; this object is nearly unique among white dwarfs in showing strong spectral features due to both carbon and hydrogen (Liebert 1983), although Thejll et al. infer that the atmosphere is dominated by helium.

[1] Steward Observatory, University of Arizona, Tucson, AZ 85721.
[2] Lunar and Planetary Laboratory, West 9th Floor, Gould-Simpson Building, University of Arizona, Tucson, AZ 85721.
[3] NASA Graduate Student Research Fellow.
[4] Guest Observer with the *International Ultraviolet Explorer* satellite, which is sponsored and operated by the National Aeronautics and Space Administration, by the Science Research Council of the United Kingdom, and by the European Space Agency.
[5] Département de Physique, Université de Montréal, C.P. 6128, Succ. A, Montréal, Québec, Canada H3C 3J7; also postal address for P. Bergeron.

Their best fit to a very complicated spectrum is achieved with models having log g between 9.0 and 9.5, implying a white dwarf mass near or above 1.2 $M_{\odot}$. In addition, it appears that Grw $+70°8247$ and perhaps other strongly magnetic white dwarfs have masses significantly larger than the average (Greenstein & Oke 1982; Liebert 1988).

Recently Bergeron et al. (1990) and Daou et al. (1990) have shown that it is possible to obtain estimates of the atmospheric parameters $T_{\rm eff}$ and log g for DA stars by fitting simultaneously line profiles of the low and higher members of the Balmer series in the manner described in the cited papers. With observed line profiles of high signal-to-noise ratio obtained with a CCD spectrophotometric detector, the technique yields atmospheric parameters of demonstrably improved accuracy for individual cases in comparison to those obtained using narrow-band colors, energy distributions, or gross equivalent widths of Balmer lines.

More recently, Bergeron et al. (1991a, hereafter BSL) have applied this technique to a large sample of some 125 DA stars with $T_{\rm eff} \geq 13{,}000$ K in an effort to determine more accurately the shape of the white dwarf mass distribution and to identify individual cases with abnormally high or low masses. Independently, Holberg, Wesemael, & Basile (1986), Holberg et al. (1989), and Kidder, Holberg, & Wesemael (1990) have been engaged in a complementary study of a sample of very hot DA (and DAO) degenerates with $T_{\rm eff} \geq 20{,}000$ K, using a somewhat similar approach. These last studies often include analysis of the Lyα profile, obtained with the *International Ultraviolet Explorer Observatory* (*IUE*). In both sets of investigations, GD 50 (WD 0346−011, KUV 898−9) clearly emerged as the object having the highest surface gravity. In their preliminary analysis, Bergeron et al. (1991b) have shown that this unusual object is about 5 σ above the mean log g of their distribution (log $g = 7.85$, $\sigma = 0.24$) and possesses a surface gravity more than +0.5 dex larger than those of the next most massive objects.

We report in this paper a joint detailed analysis of this massive star. The fits from optical and ultraviolet spectrophotometry are presented in § 2, and the implications are discussed in § 3.

2. FITS TO HYDROGEN LINE PROFILES AND THE DERIVED PARAMETERS

2.1. *Optical and Ultraviolet Observations*

An optical spectrum of GD 50 was obtained on 1989 November 8 with the Cassegrain spectrograph and a TI CCD detector attached to the Steward Observatory 2.3 m reflector. A 600 lines per mm grating yielded 8 Å resolution over a wavelength range $\lambda\lambda$3780–5280. The optical spectrum of GD 50 is displayed in Figure 1 along with the spectrum of GD 394, a DA white dwarf with a similar effective temperature and normal surface gravity. The enhanced broadening of the low Balmer lines and the near-absence of the higher members are a clear indication of the unusual high atmospheric pressure present in GD 50. Another independent, high-resolution ($\sim$1 Å) CCD spectrum of the Hβ profile was obtained on 1988 November 18 with the same telescope using a 1200 line per mm grating blazed at 5346 Å.

GD 50 was also observed with *IUE*. In constructing the Lyα profile from available SWP images we employed three small-aperture spectra (SWP 13381, 28886, and 31975) and four large-aperture spectra (SWP 11304, 28886, 29589, and 31974). Following corrections for variations in SWP camera response due to temporal variations (Bohlin & Grillmair 1988) and camera head temperature (Imhoff 1986), these spectra were co-added using appropriate scale factors for the small-aperture fluxes. Contamination of the stellar Lyα feature by geocoronal emission was avoided by using only the small-aperture fluxes to define the central regions of the line. Corrections for temporal variation largely eliminated the effect of excess flux in the red wing of the Lyα line noted in Holberg et al. (1986); consequently this "correction" was not applied here. Our resulting Lyα profile of GD 50 is displayed in Figure 2 together with that of GD 2 at a similar effective temperature.

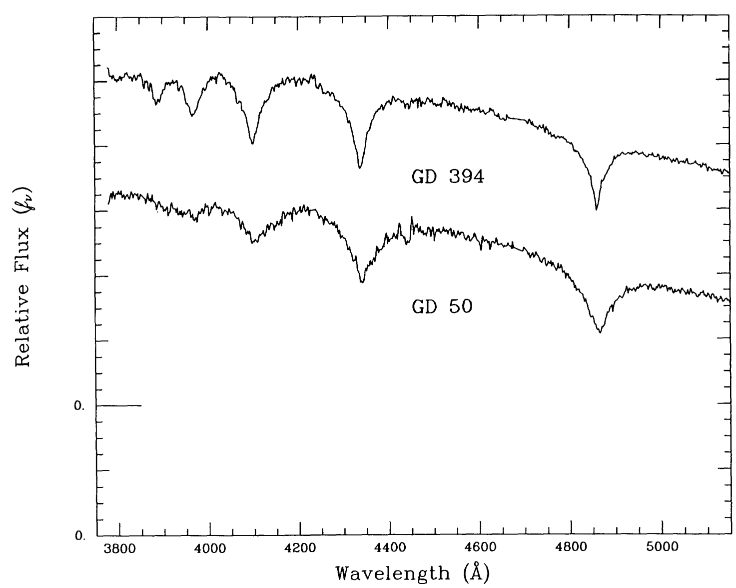

FIG. 1.—Optical spectrum of GD 50 compared to that of GD 394, a DA white dwarf with a similar effective temperature ($T_{\rm eff}$ = 38,850 K, log g = 7.81; Bergeron, Saffer, & Liebert 1990b). The spectra are normalized at 4200 Å and are shifted vertically.

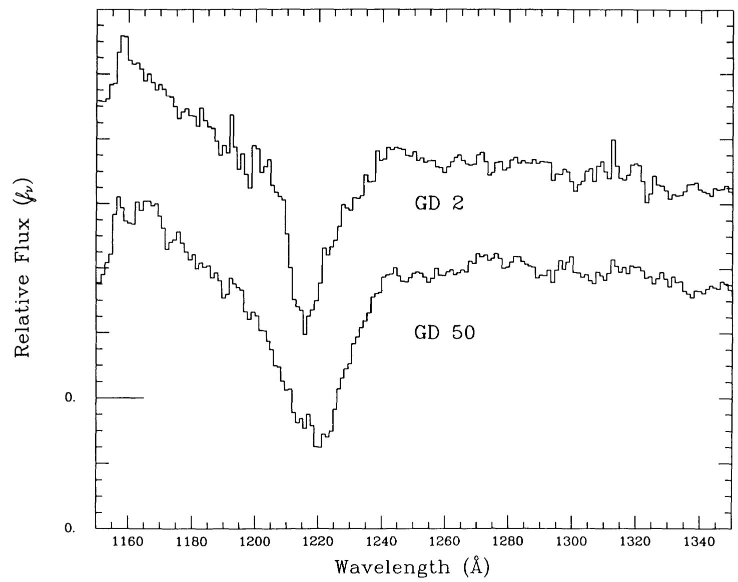

FIG. 2.—The Lyα profile of GD 50 compared to that of GD 2 ($T_{\rm eff}$ = 42,700 K, log g = 8.0; Vennes, Shipman, & Petre 1990). The spectra are normalized at 1165 Å and are shifted vertically.

2.2. *Determination of the Atmospheric Parameters*

Here we use the previously described ultraviolet and optical spectra in an effort to best constrain the effective temperature and surface gravity of GD 50. In doing this, we perform independent fits to our three sets of spectroscopic data; the 8 Å resolution observations which include the Balmer lines (Hβ through H9), the $\sim$1 Å resolution Hβ profile, and the composite Lyα *IUE* profile. All fits involve a common basic strategy. Detailed fits to the observed profiles are performed, in a least squares sense, using a grid of models covering the expected range of effective temperature and surface gravity. Best-fitting models together with associated ranges of uncertainty are then found in the $T_{\rm eff}$–log g plane. Ideally, such a procedure will lead to a single set of atmospheric parameters capable of describing all the observations within acceptable statistical limits.

The model atmospheres used for our analysis are similar to those described by Wesemael et al. (1980), which are hydrogen-line blanketed and in LTE. The thermodynamic stratifications of these models are used to calculate detailed emergent fluxes. Because of the historical development of this project, two grids of synthetic spectra were used in the initial analysis. The first one is similar to that used in the investigations of Holberg et al. (1985, 1989) and was used to analyze the 1 Å resolution Hβ profile and the Lyα *IUE* profile; a more recent grid incorporates the occupation probability formalism of Hummer & Mihalas (1988), as discussed by Bergeron et al. (1991c), and was used to analyze the 8 Å resolution Balmer line spectrum. While the fits presented here make use only of the latter grid, tests have confirmed our expectation that the predicted profiles of both the Hβ and Lyα lines, which connect relatively low-lying levels, are unaffected by the treatment of the atomic level perturbations. The higher Balmer transitions, however, whose associated levels can be strongly perturbed by neighboring particles, are dependent on the way these perturbations are treated. A detailed discussion of these aspects will be presented elsewhere.

Although we adopt a common grid of synthetic spectra for our analysis, the fitting procedures for each set of data involve a slightly different set of assumptions and techniques. For the 8 Å resolution data, we adopt a procedure described in BSL (see also Daou et al. 1990) in which a single comprehensive fit is determined simultaneously for all the observed Balmer profiles. The best fitting model is $T_{\rm eff} = 41{,}000 \pm 1000$ K and log $g = 9.00 \pm 0.15$. An independent fit to the 1 Å Hβ profile following the techniques of Kidder et al. (1990) yields $T_{\rm eff} = 42{,}400 \pm 2100$ K and log $g = 9.36 \pm 0.39$. A similar fit to the Lyα profile only yields $T_{\rm eff} = 46{,}100 \pm 2200$ K and log $g = 9.40 \pm 0.50$. The quoted error bars are all 3 σ estimates.

The range of effective temperature allowed by our three fits varies considerably from 41,000 K for the combined Balmer profiles to 46,000 K for the Lyα fit. If the full range of uncertainties associated with each fit is considered, then the effective temperature estimates range from 40,000 K to 50,000 K. Several systematic effects are potential contributors to this large uncertainty in our determination. To begin with, the observed Lyα profile contains some excess flux in the red wing with respect to the best-fit model. As mentioned, we do not use the "red wing correction" to the *IUE* fluxes discussed in Holberg et al. (1986) because our data have been temporally corrected according to Bohlin & Grillmair (1988). In principle, a new "red wing" correction could be applied which is consistent with the new *IUE* temporally corrected fluxes. Determination of such a correction is in progress but relies on a careful analysis of a dozen DA white dwarfs covering a wide range of effective temperature. Preliminary indications are that such an adjustment will reduce Lyα temperatures marginally, perhaps by 1000 K in the case of GD 50. Also, the Balmer line profiles become less sensitive to effective temperature and the resulting $T_{\rm eff}$ determination relies strongly on a precise relative flux calibration of the data. For example, although the 8 Å Hβ data look similar to the 1 Å data when compared on a similar scale, the effective temperatures obtained using the former data set are 900–2000 K cooler, depending on the fitting technique used. This shows that at the high effective temperature of GD 50, the Balmer line profile may not be a very precise temperature indicator.

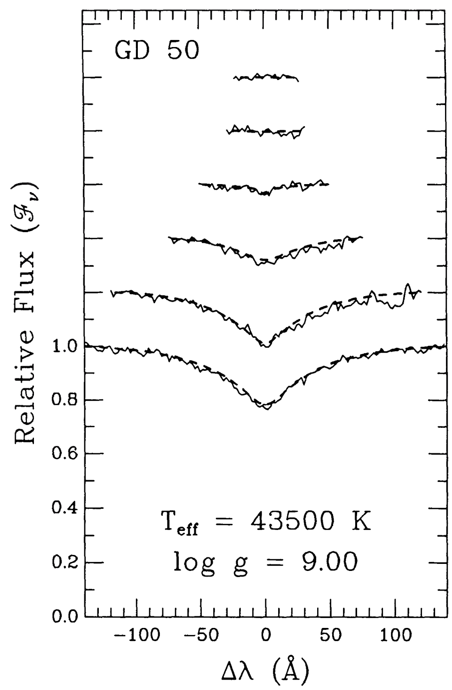

FIG. 3.—Our adopted fit to the individual Balmer lines of GD 50. The lines range from Hβ (*bottom*) to H9 (*top*) and are offset vertically from each other.

Finally, in the particular case of GD 50, we are not able to rule out completely the possiblity of residual effects from such phenomena as rotation and magnetic fields. Taking into account the above considerations, we adopt an effective temperature of $T_{eff} = 43{,}500 \pm 1500$ K for GD 50. This represents a reasonable compromise among our spectroscopic estimates and is also a good agreement with the ultraviolet continuum estimate of Finley, Basri, & Bowyer (1990; $T_{eff} = 43{,}300 + 1380; -1270$ K). We regard the Finley et al. estimate as a strong constraint on the effective temperature of GD 50 for two reasons. First, as it is a continuum-based measurement, it is largely independent of gravity. Second, it can be shown that the Finley et al. results are in good agreement with other spectroscopically determined effective temperature throughout the temperature range of interest.

All three of our determinations clearly indicate that GD 50 possesses a very high surface gravity. As discussed previously, the high Balmer lines are more sensitive to surface gravity because of pressure quenching than the lower Balmer lines and Lyα profile which are sensitive to surface gravity only through Stark broadening. The lack of high Balmer lines in the spectrum of GD 50 thus provides a severe constraint on the surface gravity. Therefore, we adopt for the surface gravity the value constrained by the analysis of the high Balmer lines, namely $\log g = 9.00 \pm 0.15$. The resulting fits to the Balmer lines and the Lyα profile are displayed in Figures 3 and 4 respectively.

2.3. *Discussion of the Results*

Other temperature and surface gravity determinations of GD 50 include (*a*) Finley et al. (1990), who fitted the SWP continuum (excluding the Lyα region) of GD 50 to obtain $T_{eff} = 43{,}330 + 1380; -1270$ K; (*b*) McMahan (1989) who fitted low-resolution optical spectra of GD 50 to obtain $T_{eff} = 34{,}330 \pm 696$ K and $\log g = 8.03 \pm 0.19$, and (*c*) Kahn et al. (1984) who relied on a much inferior observation of an Hβ profile to obtain $T_{eff} = 47{,}500 \pm 2500$ K. In addition, *UBV* photometry ($V = 14.05$, $B-V = -0.28$, $U-B = -1.19$; Landolt 1973) indicates a temperature in excess of 40,000 K. With the singular exception of McMahan (1989), the results are in adequate agreement with the effective temperature we obtain for GD 50. Comparisons with other determinations of white dwarf temperatures and gravities, including Holberg et al. (1986), Finley et al. (1990), Shipman (1979), and Koester et al. (1979), often reveal considerable variance with the results of McMahan (1989), particularly at higher temperatures.

We have also explored the possibility that the peculiar spectrum of GD 50 could be explained by rotational broadening or by a magnetic field. In order to reproduce the profiles of the high Balmer lines in a model at $T_{eff} = 43{,}000$ K with a normal surface gravity of $\log g = 8.0$, the value of $v \sin i$ needs to be increased to some 2500 km s^{-1}. However, with such a high

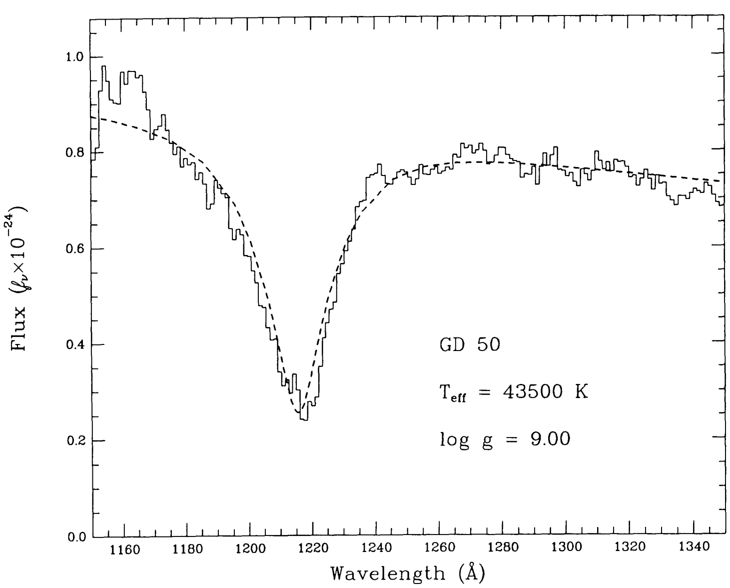

FIG. 4.—Our adopted fit to the Lyα profile of GD 50

value, the profile of the lower Balmer lines are predicted to be too broad and do not reproduce adequately the observed line profiles. Likewise, the lower Balmer line profiles in GD 50 do not resemble the flat-bottomed cores of DA stars of similar $T_{\rm eff}$ with surface magnetic fields near 1 megagauss (Liebert et al. 1983); at larger field strengths, the profiles split into Zeeman triplets. One megagauss is a conservative upper limit for any magnetic field. Thus, although we cannot completely rule out that one or both mechanisms are present at some level, an unusually high surface gravity for GD 50 remains the most plausible model to explain its spectrum.

3. ASTROPHYSICAL IMPLICATIONS

Our derived value of log g corresponds to a mass of approximately $1.2 + 0.07; -0.08\ M_\odot$ and a radius of $0.0057 \pm 0.0009\ R_\odot$, if we use the evolutionary models of Wood (1990) with a CO core and a helium envelope, for the appropriate effective temperature near 43,000 K. This value for the mass corresponds to a predicted gravitational redshift velocity of 134 km s^{-1}. At 1.2 $M_\odot$, GD 50 has a mass approximately 0.3 $M_\odot$ higher than that inferred for two stars of next highest gravity in the sample of BSL. One of the latter is the likely Pleiades cluster member LB 1497 (Greenstein 1974), a star which it can be assumed has evolved from a main-sequence progenitor with a mass larger than 6 $M_\odot$. Likewise, in the analyses of hot DA white dwarfs by Holberg et al. (1986) and Holberg et al. (1989), only the binary HZ 43 was identified as fitting a surface gravity near log $g = 8.5$, again implying a mass near 0.8–0.9 $M_\odot$.

The mass derived for GD 50 assuming a CO core is in fact high enough to consider the possibility that the core is instead composed of ONeMg, as mentioned in § 1. If this were possible, however, then an appropriate mass-radius relation from an evolutionary model with an ONeMg core and external CO and He layers should be used to determine the total stellar mass. While such evolutionary models are, to our knowledge, not available, examination of the predictions of zero-temperature models (Hamada & Salpeter 1961) suggests that the mass would be smaller by at most several hundredths of a solar mass. The mass we have inferred and its uncertainty does not leave us with a clear-cut distinction between these possibilities.

Regardless of the core composition, one may argue that such a very hot white dwarf with a mass near 1.2 $M_\odot$ should be very young in its total stellar age, if it is due to the evolution of a single star. If a monotonic relationship between the initial stellar mass and the final mass applies to white dwarfs of the Galactic disk population, one would expect that the progenitor of GD 50 should have been more massive than that of LB 1497 in the Pleiades since the former has both the higher remnant mass and is a hotter white dwarf with a shorter cooling time. Due to the lack of precision in the relationship between initial mass and final mass, we cannot estimate precisely the total stellar age of GD 50 other than to suggest that it might be of order 10^7 yr (as opposed to some 7×10^7 yr for the Pleiades).

It is then reasonable to ask if GD 50 is associated with any known young stellar association, moving group, or region of ongoing or recent star formation. Inspection of the Palomar Sky Survey prints suggests that GD 50 does not lie in or near such a region. Moreover, GD 50 was cataloged by the Lowell Observatory as a blue object of only slight proper motion. Its estimated proper motion (EPM) class 2 implies only a motion of $0.1-0.2$ arcsec yr^{-1} at a position angle $170 \pm 5°$ (Giclas, Burnham, & Thomas 1965). The object does not appear in any of the Luyten lists of stars of measured proper motion. The coarse astrometric information is not sufficient to associate it with any young kinematic group or cluster. We note that GD 50 lies some 25° south of the Pleiades cluster at a right ascension similar to that of LB 1497. However, this implies a physical separation on the plane of the sky of some 60 pc from the cluster. From our adopted atmospheric parameters and the measured V magnitude of Landolt (1973), we predict a distance of only 37 pc with a corresponding parallax of 0."027. This would place GD 50 well into the foreground of the Pleiades whose distance is 140 pc. Thus, it seems unrealistic to pursue further the possibility that GD 50 is associated with the Pleiades cluster, especially given the likelihood that its age may be considerably younger. One might thus be faced with the question as to whether a fairly massive (6–8 $M_\odot$) star could have formed in relative isolation. Given the lack of precise astrometric data and the existence of apparently massive O- and B-type stars even at large distances from the Galactic plane, this might not pose an unprecedented dilemma.

Alternative scenarios involving close binary evolution would allow GD 50 both to be old and to have a CO core, despite its high mass. One possibility is that GD 50 was a cataclysmic variable, having perhaps accreted a substantial amount of material from a nondegenerate companion which is no longer present or detectable. An alternative possibility is that GD 50 has been the product of a prior merger of a close pair of white dwarfs, whose mean mass was about 0.6 $M_\odot$. Binary, common-envelope evolution scenarios producing a close pair with CO cores or one each of CO and helium might be suitable (Iben & Tutukov 1990). In particular, the combined mass of the recently discovered, close binary DA system L870−2 (Saffer, Liebert, & Olszewski 1988) is within about 0.2 $M_\odot$ of the value required here (Bergeron et al. 1989).

It might be anticipated that a dynamical merger of two white dwarfs would result in a rapidly rotating product. However, we note that the line profiles of GD 50 are so broad that any upper limits on its possible rotation rate (v sin i) are difficult to establish. Second, if one component of the close binary were a helium degenerate, a long phase ($\geq 10^8$ yr) of helium burning would occur, during which time the star would swell to a much larger radius. It is possible that such a phase would result in the loss of substantially all of the angular momentum (Iben 1990).

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