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# DISCOVERY OF AN ULTRACOOL WHITE DWARF COMPANION

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## ABSTRACT

The discovery of a low-luminosity common proper-motion companion to the white dwarf GD 392 at a wide separation of 46″ is reported. *BVRI* photometry suggests a low temperature ($T_{\rm eff} \sim 4000$ K), while *JHK* data strongly indicate suppressed flux at all near-infrared wavelengths. Thus, GD 392B is one of the few white dwarfs to show significant collision-induced absorption due to the presence of photospheric $H_2$ and the first ultracool white dwarf detected as a companion to another star. Models fail to explain GD 392B as a normal-mass white dwarf. If correct, the cool companion may be explained as a low-mass white dwarf or unresolved double degenerate. The similarities of GD 392B to known ultracool degenerates are discussed, including some possible implications for the faint end of the white dwarf luminosity function.

*Subject headings:* binaries: general — stars: fundamental parameters — stars: individual (GD 392) — white dwarfs

## 1. INTRODUCTION

White dwarfs are evolved stars that have exhausted their nuclear fuel and are supported by electron degeneracy pressure. They are destined to cool to ever lower temperatures over billions of years as the end product of most stars in the Galaxy, main-sequence stars with $M \lesssim 8\ M_\odot$. Next to low-mass stars, they are the most common stellar objects in the Milky Way, providing a window into the history of stellar evolution and star formation in the Galaxy.

Ultracool white dwarfs ($T_{\rm eff} < 4000$ K) have been of much interest to researchers in recent years for several reasons. First, it remains an unanswered question as to whether cool white dwarfs are a significant component of Galactic halo dark matter (Hansen & Liebert 2003). Second, the ages and compositions of cool white dwarfs have obvious implications for the age and evolution of the disk, bulge, and halo components of the Galaxy. Finally, the distribution and origins of atmospheric and core compositions of the coolest white dwarfs are still not well understood.

In this paper the discovery of GD 392B, a common proper-motion companion to the helium white dwarf GD 392 [WD 2058+342; R.A. = $21^{\rm h}00^{\rm m}21\overset{\rm s}{.}5$, decl. = $+34°26'20''$ (J2000.0)], is discussed. The spectral energy distribution (SED) of GD 392B strongly suggests flux deficiency redward of 1 $\mu$m, a $T_{\rm eff} < 4000$ K, and possibly a helium component in its atmosphere as well (Bergeron & Leggett 2002). Tentative stellar parameters are derived for GD 392B based on the data and different assumptions about the mass of the primary. Possible implications based on the model fit parameters and similarities to known ultracool white dwarfs are then discussed.

## 2. OBSERVATIONS AND DATA REDUCTION

### 2.1. *Photometry*

Near-infrared data on the GD 392 system were obtained at Lick Observatory in 2003 June and August. *JHK*′ images were acquired using the Gemini camera (McLean et al. 1993) on the 3 m Shane telescope. Total observation time was 7.5 minutes at each filter, consisting of 15 s exposures in a repeated five-point dither pattern. Multiple infrared photometric standard stars from Hunt et al. (1998) and Hawarden et al. (2001) were observed twice during the night. The conditions in August were very good, with clear skies and average seeing of $1\overset{''}{.}3$. In June, the weather was good but the average seeing was $1\overset{''}{.}8$. A few *K*-band images were taken at Mauna Kea in 2003 July using the Near-Infrared Camera (NIRC; Matthews & Soifer 1994) on the 10 m Keck I telescope. Images consisted of 10 s exposures for the primary and 50 s for the secondary. Observing conditions were poor, with considerable cloud cover and seeing of $0\overset{''}{.}6$. Optical data were obtained at Lick Observatory in 2003 July and September. *BVRI* images were acquired with the CCD camera on the 1 m Nickel telescope. Total exposure time was 5 minutes at each filter, and photometric standard stars from Landolt (1983) were observed immediately prior to the GD 392 system. Conditions in August were excellent, with clear skies and seeing of $0\overset{''}{.}9$. In July, the sky was clear but the average seeing was $1\overset{''}{.}2$.

Images were reduced using standard programs in the IRAF environment. Optical images were filtered clean of bad pixels and cosmic rays in the area of interest, then flat-fielded with a normalized dome flat. Near-infrared images were sky-subtracted, flat-fielded, registered, and averaged into a single image at each wavelength.

Straightforward aperture photometry was used, including air-mass/extinction corrections, for *BVRIJHK* measurements of the primary. Using a circular aperture centered on the target star and an annulus on the surrounding sky, both the flux and the signal-to-noise ratio (S/N) were calculated for a range of apertures from 1 to 4 FWHMs. The target flux was measured at or near the aperture size that produced the largest S/N. In this way the flux of all targets was measured, including standard stars. A large aperture ($d \sim 6''$) was used for all calibrators, and flux measurements for science targets were corrected to this standard aperture to account for the smaller percentage of the total flux contained within apertures smaller than the standard.

Extracting all photometry for GD 392B was complicated by the presence of a nearby background star (Fig. 1). In a single subtraction *J*-band image, the separation between GD 392B and the background star was measured to be $1\overset{''}{.}8 \pm 0\overset{''}{.}1$ at a position angle (P.A.) of $196° \pm 3°$. Since even small aperture

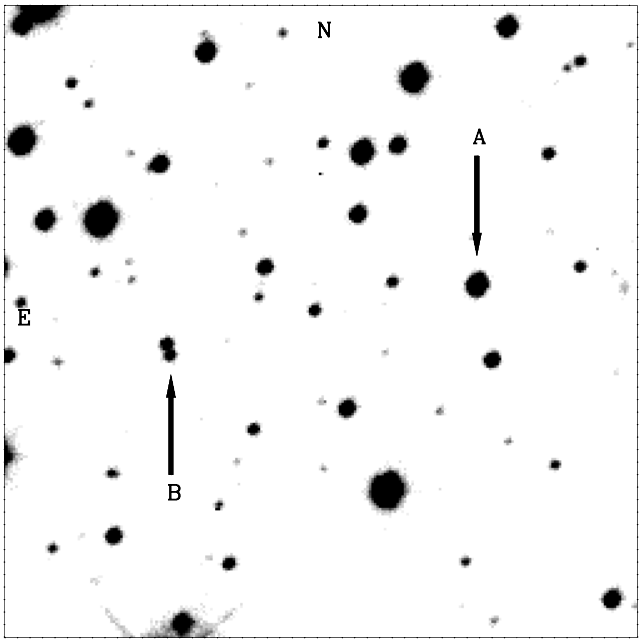


FIG. 1.—*I*-band (0.80 $\mu$m) image of the GD 392 system obtained with the CCD camera on the Nickel 1 m telescope on 2003 September 15. The scale is 0″.36 pixel$^{-1}$, and the frame is 92″ on a side. The object labeled "A" is GD 392, and the object labeled "B" is the cool white dwarf companion, GD 392B [(R.A. = $21^h00^m25^s.1$, decl. = $+34°26'09''$ (J2000.0)]. About 1″.8 northeast of the secondary is an unrelated background K dwarf. Because of its proper motion, GD 392B and the background K star are moving closer together.

flux measurements of GD 392B would be contaminated by light from the background star, the IRAF package DAOPHOT was employed to fit the point-spread function (PSF) of both stars simultaneously and extract their magnitudes. Since DAOPHOT is sensitive to the separation and brightness ratio of two sources with overlapping PSFs, the optical and infrared data were broken into two sets: primary data for which the FWHMs in the reduced images were less than 1″.8 and secondary data for which they were greater than or equal to 1″.8. This is an especially important consideration in the infrared, where the brightness ratio of GD 392B and the background star is far from unity. All photometric data are listed in Table 1, and the adopted values used for the analysis are listed in Table 2. The secondary data were not included in the analysis because of the uncertainty in PSF fitting for sources separated by less than 1 FWHM—the data are consistent with the adopted values to within 1–2 $\sigma$ and are included for completeness. Conversions between near-infrared filter sets were not performed for three reasons: (1) the corrections are typically very small (Leggett 1992; Carpenter 2001); (2) the colors of GD 392B are drastically different from the colors of standard stars used to derive the transformations; and (3) the near-infrared photometry errors in Table 1 are likely to be several times larger than any corrections.

Because of the poor weather conditions, there was only a single NIRC frame acquired with GD 392B on the chip, three frames containing GD 392A, and several sky frames. Since the common proper-motion system is separated by more than the 39″ field of view, the binary pair could not be observed simultaneously. The reduced images of the primary and secondary contained three field stars in common. Aperture photometry was performed on these stars twice: once with GD 392A as a calibrator and again using the three field stars as calibrators for GD 392B and the background star. These intermediate calibrator stars had a standard deviation of only a few percent in their measured relative fluxes between the two reduced images. GD 392B and the background star were spatially resolved from each other in this observation.

The S/N in the primary data set was greater than 30 for both stars in the reduced images at all wavelengths with the exception of the following. In the Gemini images, the S/N was calculated to be 8.6 at *H* and 3.7 at *K′* for GD 392B (from the extracted DAOPHOT data). In the Nickel data, the S/N at *B* was 11.4 for GD 392B and 15.1 for the background star. In the single-subtraction flat-fielded NIRC *K* frame, the S/N for GD 392B was 5.8.

TABLE 1
PHOTOMETRIC DATA FOR THE GD 392 SYSTEM

| Band | $\lambda_0$ ($\mu$m) | GD 392A (mag) | GD 392B (mag) | K star (mag) |
|---|---|---|---|---|
| *B* | 0.44 | 15.71 | 20.82 ± 0.09 | 20.52 ± 0.07 |
| | | 15.79 | 20.74 ± 0.06 | 20.51 ± 0.06 |
| *V* | 0.55 | 15.67 | 19.50 ± 0.03 | 19.31 ± 0.03 |
| | | 15.69 | 19.59 ± 0.04 | 19.44 ± 0.04 |
| *R* | 0.64 | 15.61 | 18.80 ± 0.02 | 18.55 ± 0.02 |
| | | 15.63 | 18.83 ± 0.04 | 18.54 ± 0.04 |
| *I* | 0.80 | 15.62 | 18.06 ± 0.02 | 17.73 ± 0.02 |
| | | 15.69 | 18.18 ± 0.04 | 17.81 ± 0.04 |
| *J* | 1.25 | 15.73 | 17.73 ± 0.07 | 16.79 ± 0.06 |
| | | 15.77 | 17.64 ± 0.06 | 16.75 ± 0.05 |
| *H* | 1.65 | 15.79 | 18.16 ± 0.09 | 16.16 ± 0.05 |
| | | 15.81 | 17.93 ± 0.10 | 16.17 ± 0.05 |
| *K′* | 2.12 | 15.86 | 18.49 ± 0.25 | 16.09 ± 0.07 |
| | | 15.88 | 18.64 ± 0.29 | 16.10 ± 0.06 |
| *K* | 2.21 | . . . | 18.53 ± 0.20 | 15.99 ± 0.05 |

NOTES.—Photometric uncertainties for GD 392A are 3%. The first values listed for each filter are the primary data set used in the analysis for GD 392B. All other data are secondary (§ 2.1).

## 2.2. *Spectroscopy*

A 0.38–1.0 $\mu$m spectrum was obtained using the Low Resolution Imaging Spectrograph (LRIS; Oke et al. 1995) in 2003 October at Mauna Kea on Keck I by C. Steidel, D. Erb, and N. Reddy. The setup consisted of the 300/5000 Å grism on the blue side and the 400/8500 Å grating on the red side, separated at 6650 Å by a dichroic beam splitter. The spectra of both stars were spatially resolved from each other in the

TABLE 2
ADOPTED MAGNITUDES AND FLUXES FOR GD 392B

| Band | $\lambda_0$ ($\mu$m) | Magnitude | $F_\lambda$ ($10^{-16}$ W m$^{-2}$ $\mu$m$^{-1}$) |
|---|---|---|---|
| *B* | 0.44 | 20.82 ± 0.09 | 2.95 ± 0.24 |
| *V* | 0.55 | 19.50 ± 0.03 | 5.67 ± 0.16 |
| *R* | 0.64 | 18.80 ± 0.02 | 6.47 ± 0.12 |
| *I* | 0.80 | 18.06 ± 0.02 | 6.69 ± 0.12 |
| *J* | 1.22 | 17.73 ± 0.07 | 2.47 ± 0.15 |
| *H* | 1.63 | 18.16 ± 0.09 | 0.62 ± 0.05 |
| *K* | 2.19 | 18.51 ± 0.23 | 0.16 ± 0.03 |

NOTES.—*BVRI* is on the Johnson-Cousins system and *JHK* is on the Johnson-Glass system, collectively known as the Johnson-Cousins-Glass system (Bessell & Brett 1988; Bessell 1990). Conversions between near-infrared filter sets were ignored (§ 2.1).

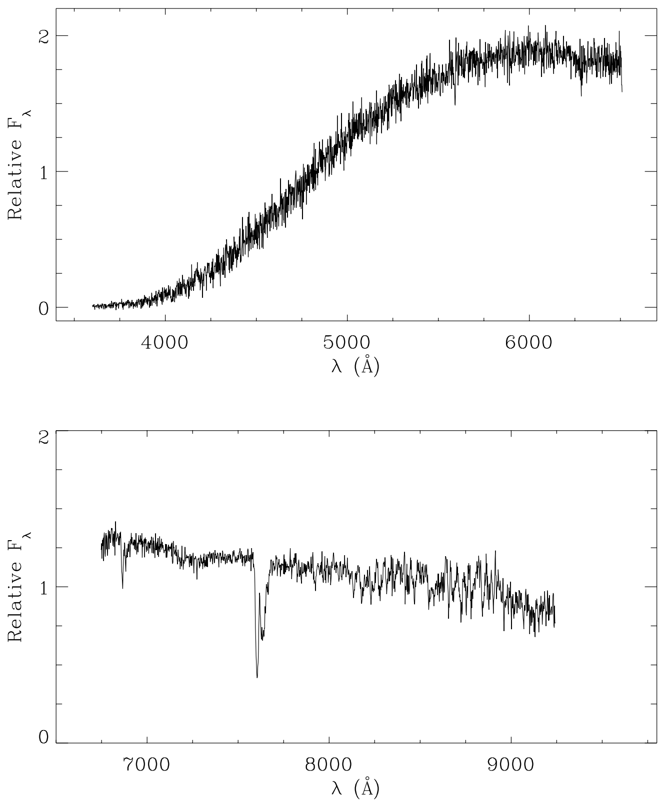


FIG. 2.—Optical spectrum of GD 392B taken with LRIS. The data are not flux-calibrated, but the overall shape should be fairly accurate (Fig. 3). The only real features are those at 6870 and 7590 Å and are due to telluric $O_2$.

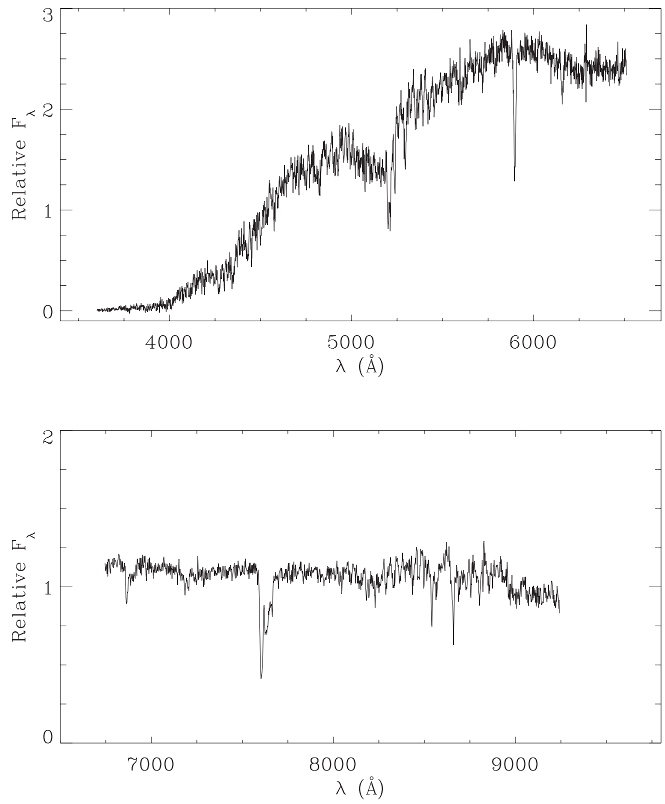


FIG. 3.—Optical spectrum of the nearby background K star. The strength of the MgH feature centered around 5100 Å may indicate a metal-poor atmosphere (Jacoby et al. 1984; Reid & Hawley 2000).

observation. The spectral images were cleaned of bad pixels and cosmic rays, then flat-fielded using an internal halogen lamp. A spectrum of the sky was extracted at two positions for each wavelength region, averaged, and then subtracted from the spectrum of each star. Standard programs in IRAF were used to extract the spectra of both GD 392B and the background star.

The lamp used to flat-field the spectral images is itself spectrally nonuniform and has a strong rise from 4500 to 7500 Å.[1] Hence, the instrument and chip response were removed by flat-fielding, but the remaining shape was a convolution of the stellar spectra and the "flat" lamp. The background star appears to be a K dwarf whose exact spectral type cannot be established from photometry because its reddening is unknown and the low-resolution spectrum precludes the line measurements necessary for a determination. Spectra extracted without flat-fielding confirm that the flux of both GD 392B and the K star rises toward the dichroic cutoff near 6600 Å (a fact corroborated by the photometry). Attempting to reconstruct the true shape of the continua, the reduced spectra were multiplied by a blackbody with a temperature similar to that of the halogen flat lamp. This information was obtained from the manufacturer.[2] The resultant spectra are shown in Figures 2 and 3.

## 3. PROPER MOTION OF GD 392A AND GD 392B

A wide-field infrared proper-motion survey for low-mass stellar and substellar companions to nearby white dwarfs is being completed (Farihi et al. 2003). Because the observations are being conducted primarily at the $J$ band (1.25 $\mu$m), the survey is particularly sensitive to cool objects such as late M, L, and early T-type dwarfs. A near-infrared search is also sensitive to cool white dwarfs. This survey's sensitivity is slightly less for cool degenerates that suffer collision-induced absorption (CIA) opacity at this wavelength relative to those that do not. In general, common proper-motion companions brighter than $J = 19$ mag can be detected.

To measure proper motions and detect companions, GEOMAP is used. This is a standard program in the IRAF environment, which generates a transformation between two sets of coordinates corresponding to sources in the same field at two different epochs. In this way proper-motion stars can be identified and their motions measured against the near zero motion of background stars and galaxies, which provide a measure of the standard error.

The common proper-motion companion to GD 392 (WD 2058+342; Greenstein 1984; Greenstein & Liebert 1990; Wesemael et al. 1993) was detected in a routine examination of the digitized POSS I and POSS II plates for confirming identity, proper motion, and coordinates of the primary for a finder chart prior to an observing run. A simple blinking of POSS I and POSS II frames reveals the comoving companion at a separation of 46.″2 and a P.A. of 102.°5 (Fig. 1). Measurement of proper motion between POSS epochs reveals that both GD 392A and GD 392B have the same proper motion over a 41 yr baseline, namely, $\mu = 0.''17 \pm 0.''01$ yr$^{-1}$ at $\theta = 44° \pm 5°$. Furthermore, astrometric analysis of 2003 infrared images confirms that the separation and P.A. between primary and secondary have remained constant since 1951. The USNO-B1.0 catalog (Monet et al. 2003) gives a proper

[1] See http://www2.keck.hawaii.edu/realpublic/inst/lris/flats.html.
[2] See http://www.oriel.com/tech/curves.htm.

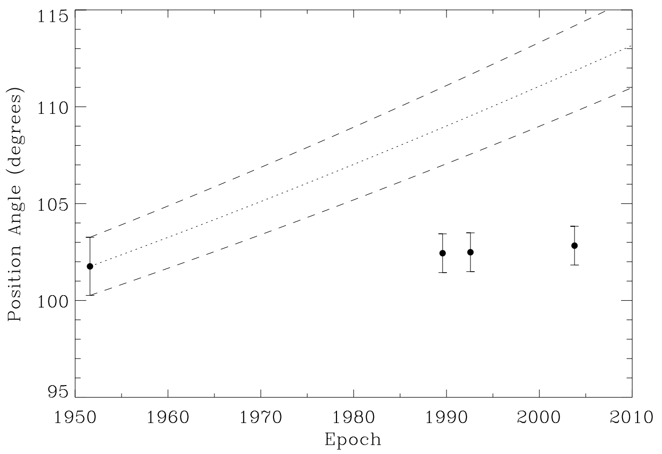


FIG. 4.—Measured P.A. of the GD 392 system at several epochs spanning 52 yr. Dashed lines bound a region in which one would expect to find GD 392B were it a stationary background object. The error in P.A. includes uncertainty in the difference of two centroids in a given image plus uncertainty in the alignment accuracy of the image itself. The 2003 data point is from an infrared image, and the other three data points are from the digitized POSS I and POSS II plates.

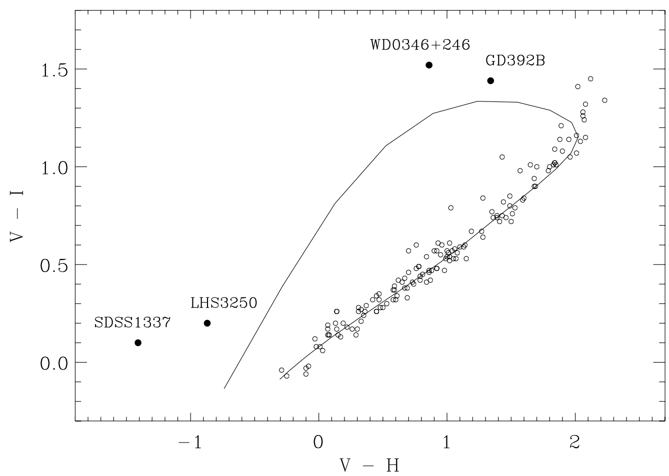


FIG. 5.—$V-I$ vs. $V-H$ color-color diagram including all known ultracool white dwarfs with published infrared photometry (SDSS 1337+00 does not have a $K$-band magnitude in the literature, which is why $H$ is used here). The solid line represents $\log g = 8$ hydrogen atmosphere cooling tracks all the way down to 2000 K at bottom left (P. Bergeron 2002, private communication). The turnoff corresponds to $T_{\rm eff} \sim 4000$ K. Open circles represent cool white dwarfs from Bergeron et al. (2001).

motion of $\mu = 0''.168 \pm 0''.002$ yr$^{-1}$ at $\theta = 42^\circ.6 \pm 0^\circ.7$ for GD 392, and no value is given for the companion. Giclas et al. (1965) published a detected proper motion of $0''.1$ yr$^{-1} \leq \mu \leq 0''.2$ yr$^{-1}$ at 45° for the primary. Both of these measurements are consistent with the value presented in this paper. Figure 4 shows the unchanging P.A. of the pair over several epochs.

At a nominal distance of 50 pc (see § 4.2), the proper motion of the pair gives $v_{\rm tan} = 40$ km s$^{-1}$, and thus there is no reason to suspect that this system is not a member of the local disk population.

## 4. RESULTS

### 4.1. *SED and Temperature of GD 392B*

Despite some relatively low S/N photometry on GD 392B in the near-infrared, there are seven independent measurements at these longer wavelengths, three of these at 2.2 $\mu$m (Table 1). In stark contrast with the similar optical magnitudes and colors, GD 392B appears roughly 1.0 mag fainter than the nearby background K star at 1.2 $\mu$m, 2.0 mag fainter at 1.6 $\mu$m, and 2.5 mag fainter at 2.2 $\mu$m in all the measurements.

The optical and infrared colors of GD 392B point strongly toward an ultracool white dwarf with strong CIA longward of 1 $\mu$m. No other stellar object could be so red in $V-I$ and yet blue in $I-K$ (Bergeron et al. 1995; Hansen 1998; Harris et al. 1999; Saumon & Jacobson 1999; Hodgkin et al. 2000; Oppenheimer et al. 2001). The optical spectrum confirms that GD 392B is a featureless DC star (Fig. 2). Hence, GD 392B must be a very cool white dwarf.

Plotting GD 392B on a $V-I$ versus $V-H$ color-color diagram, one sees that it is located beyond the turnoff for $\log g = 8.0$ pure hydrogen atmosphere white dwarfs, which corresponds to $T_{\rm eff} \sim 4000$ K (Fig. 5). There are only three other ultracool white dwarfs in the literature for which infrared photometry is available: WD 0346+246, LHS 3250, and SDSS 1337+00 (Harris et al. 1999, 2001; Hodgkin et al. 2000; Bergeron & Leggett 2002). GD 392B's optical colors are strikingly similar to those of WD 0346+246 (Oppenheimer et al. 2001). Although they have almost identical optical colors, GD 392B appears to have more flux in the near-infrared than does WD 0346+246. From recent model atmosphere analyses of the three aforementioned stars, it is possible that GD 392B is warmer, has different gravity, and/or contains a different ratio of hydrogen to helium in its atmosphere than does WD 0346+246 (Bergeron 2001; Bergeron & Leggett 2002).

The best way to estimate the temperature of GD 392B is to fit models to the *BVRIJHK* photometry. To evaluate its SED, the magnitudes were converted into isophotal or average fluxes, following the method of Bergeron et al. (1997). Different fits to the data were tried using the pure hydrogen and mixed H/He atmosphere model grids of P. Bergeron (2003, private communication). As in the case of WD 0346+246 (Bergeron 2001; Oppenheimer et al. 2001), pure hydrogen and mixed atmosphere models fail to reproduce the SED of GD 392B in detail. And like Oppenheimer et al. (2001), a low-gravity solution appears to provide a decent fit to the data. In fact, every solution at $\log g > 7.0$ seems to provide optical colors that are too blue (too much CIA) or infrared colors that are too red (too little CIA). As shown in Figure 6, a decent fit is achieved at $\log g = 7.0$, $T_{\rm eff} = 3500$ K, and $N_{\rm H}/N_{\rm He} = 10$. Also shown in Figure 6 is a blackbody of the same temperature scaled to the peak flux of GD 392B—relative to the blackbody, the SED of GD 392B appears suppressed at wavelengths longer than 8000 Å and enhanced at shorter wavelengths.

Because GD 392B is a companion to a previously studied white dwarf, it should be possible to deduce the distance to this system and use it to constrain stellar radius $R$ and $M_V$. One must keep in mind that the model-predicted temperature of GD 392B will depend on its mass and atmospheric composition and thus cannot be known exactly at present. In § 4.2 a range of possibilities is explored.

### 4.2. *Stellar Masses of the GD 392 System*

Using basic relations between luminosity and flux, one can calculate a radius for GD 392B if its distance and $T_{\rm eff}$ are known. To obtain a distance, the *BVRIJHK* photometry of the primary (Table 1), GD 392, was fitted with pure helium model grids (P. Bergeron 2002, private communication), and its measured SED was integrated directly. The model fit provides a $T_{\rm eff}$, and integrating the SED of GD 392 yields a total flux.

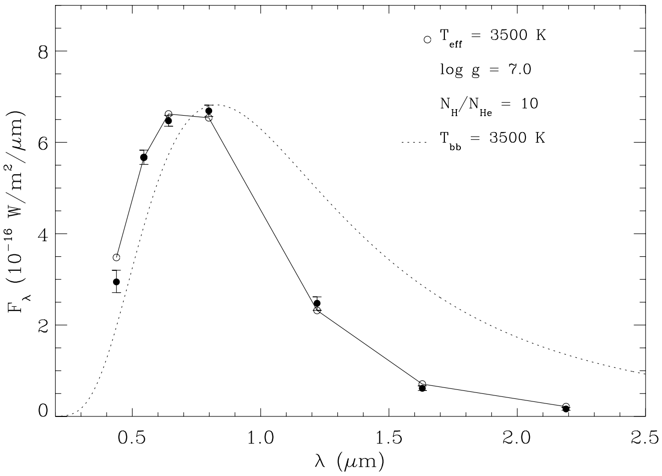


FIG. 6.—SED of GD 392B as determined from *BVRIJHK* photometry. Filled circles with error bars represent the data. Open circles and the solid line represent the mixed atmosphere model fit; only the *B* data point is discrepant. The dotted line is a blackbody of the same temperature, demonstrating that the SED is reshaped by CIA.

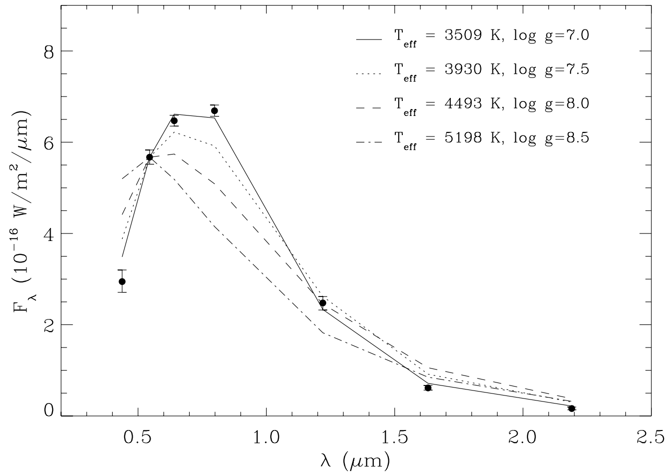


FIG. 7.—Model fits to GD 392B at 57.8 pc with $N_H/N_{He} = 10$. All but the lowest gravity case fail to reproduce the photometric measurements.

A radius must be specified in order to calculate a distance to the primary. The model fit to the SED of GD 392 does not provide a radius determination because the colors of a DB star are largely unaffected by gravity. Hence, one is forced to make various assumptions for $\log g$. Table 3 lists stellar parameters for GD 392 with various gravities and thus distances. In the literature, GD 392 has been noted as a DB5 (Greenstein 1984), DBA?4 (Greenstein & Liebert 1990), and finally a DB5 again while explicitly stating "revised from Greenstein & Liebert (1990)" (Wesemael et al. 1993). The optical and infrared photometric data presented here are more consistent with a DB4 than a DB5. Good agreement between model and measured colors is acheived at $T_{eff} = 11,625$ K (regardless of $\log g$), which actually corresponds to DB4.5. This is the temperature used in all calculations for the parameters of GD 392. For each distance estimate to the GD 392 system, there is an analytic constraint on $RT_{eff}^2$ for GD 392B. It is also critical that the model-predicted parameters, such as $M_V$, and optical and infrared colors corresponding to each combination of $R$ and $T_{eff}$, fit the photometric data on GD 392B.

If GD 392 is an average-mass white dwarf ($\log g = 8.0$), a solution is found almost identical to the preliminary fit in Figure 6. That is, at 57.8 pc GD 392B must have a temperature near 3500 K and a very large radius—either an unresolved binary or a low-mass white dwarf. This model fit is consistent with the measured colors (excepting $B-V$; see § 4.3) and matches the absolute magnitude of the secondary at this distance; in fact, only a low-gravity solution appears to provide such agreement between measured and predicted fluxes. In Figure 7, four fits are shown satisfying the $M_V$ constraint at 57.8 pc for a range of gravities. It is clear that only the $\log g = 7.0$ fit comes near to matching the photometry. Although these fits have all been scaled to match the flux at 0.55 $\mu$m, the obvious discrepancies of the higher gravity solutions occur at any scaling; they predict too little flux in the optical or too much flux in the near-infrared. In addition, the $\log g \geq 7.5$ fits do not satisfy the $RT_{eff}^2$ constraint at this distance. This scenario is instructive for two reasons. One is that there is no independent reason to suspect that GD 392 is anything but an average-mass white dwarf. In fact, the spectroscopic mass distribution of DB stars peaks at 0.59 $M_\odot$, with a very small dispersion of 0.06 $M_\odot$ (Beauchamp et al. 1996). The other reason is that the failure of the higher gravity fits to match the data persists for any reasonable distance estimate.

Assuming that the primary is a higher-than-average–mass white dwarf ($\log g \geq 8.5$) results in serious discrepancies between model-predicted and measured colors for GD 392B. This disagreement appears to be insensitive to the type of atmosphere in the models. Shown in Figure 8 is a model fit for GD 392B at 40.4 pc. Higher gravity solutions at this distance

TABLE 3

Possible Stellar Parameters for GD 392A

| $T_{eff}$ = 11,625 K | $\log g = 8.0$ | $\log g = 8.5$ | $\log g = 9.0$ |
|---|---|---|---|
| $d$ (pc) | 57.8 | 40.4 | 25.9 |
| $M/M_\odot$ | 0.59 | 0.90 | 1.19 |
| $R/R_\odot$ | 0.0127 | 0.0089 | 0.0057 |
| $M_V$ | 11.87 | 12.65 | 13.61 |
| $M_{bol}$ | 11.20 | 11.98 | 12.93 |
| $\log(L/L_\odot)$ | −2.58 | −2.89 | −3.27 |
| Cooling age (Gyr) | 0.45 | 0.91 | 1.78 |

Note.—Assuming $\log g \leq 7.5$ for the primary leads to unphysical solutions for the secondary.

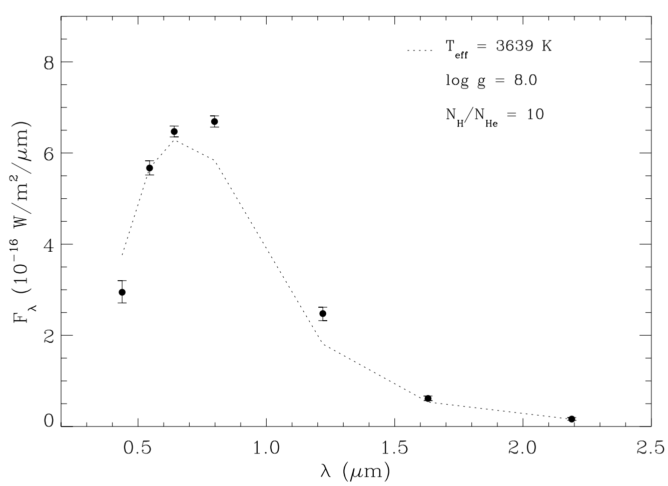


FIG. 8.—Model fit to GD 392B at 40.4 pc. The failure of the models to fit the data points persists for both higher gravities and different amounts of photospheric helium.

TABLE 4
POSSIBLE STELLAR PARAMETERS FOR GD 392B

| Parameter | $d$ = 57.8 pc | $d$ = 40.4 pc[a] | $d$ = 25.9 pc[a] |
|---|---|---|---|
| $T_{\rm eff}$ (K) | 3509 | 3639 | 3875 |
| $\log g$ | 7.00 | 7.95 | 8.72 |
| $M/M_\odot$ | 0.153 | 0.576 | 1.066 |
| $R/R_\odot$ | 0.0205 | 0.0133 | 0.0075 |
| $M_V$ | 15.69 | 16.47 | 17.43 |
| $M_{\rm bol}$ | 15.35 | 16.14 | 17.27 |
| $\log(L/L_\odot)$ | −4.24 | −4.56 | −4.94 |
| Cooling age (Gyr) | 2.92 | 9.92 | 8.62 |

NOTE.—No satisfactory model fit is found for anything but a low surface gravity white dwarf at approximately 58 pc (see § 4.2).
[a] These solutions show large discrepancies with the measured colors of GD 392B but have been included for the sake of completeness.

or closer are worse and are not shown for the sake of brevity. Problems arise as well if one assumes that the primary is a lower-than-average–mass white dwarf ($\log g \leq 7.5$). This leads to extreme low-gravity solutions for GD 392B, and the models used here do not include gravities below $\log g = 7.0$. Table 4 lists all resulting fits for GD 392B.

While the possibility exists that GD 392B is an unresolved binary or helium core white dwarf, this is uncertain until the distance to the system is known with sufficient precision and a good model fit to its SED is achieved. It seems very unlikely that GD 392B could have such an unusually low mass as 0.15 $M_\odot$, but it cannot be ruled out, either. It is conceivable that a good model fit with a much higher $T_{\rm eff}$ (hence predicting a smaller radius and a larger mass) could show good agreement with the measured colors of GD 392B. All models used here do not give such agreement. A parallax measurement of the primary is currently in progress (H. Harris 2003, private communication).

### 4.3. *Atmospheric Composition of GD 392B*

All attempts to fit the SED of GD 392B with mixed H/He atmosphere models having $N_{\rm H}/N_{\rm He} < 10$ are problematic. In fact, for all temperatures and gravities, the same problem mentioned previously occurs; colors too blue in the optical and/or too red in the infrared to fit the measured photometry, given the absolute magnitude constraint. The only possible exception is the pure hydrogen models at $\log g = 7.0$. Shown in Figure 9 are several model fits with varying ratios of H/He for the lowest gravity case. Only the pure hydrogen and the $N_{\rm H}/N_{\rm He} = 10$ models provide any kind of decent fit to the data. However, the pure hydrogen fit has one minor fault when compared to the mixed atmosphere fit: it predicts an $M_V$ corresponding to 57.8 pc but does not precisely fit the $RT_{\rm eff}^2$ constraint. The $N_{\rm H}/N_{\rm He} = 10$, $T_{\rm eff} = 3509$ K solution comes very close to hitting all the data points except $B$ and satisfies all constraints surprisingly well at 57.8 pc. There currently exists a discrepancy between model-predicted and measured $B$-band fluxes; this wavelength is excluded from fits to the energy distributions of very cool hydrogen atmosphere white dwarfs (Bergeron et al. 1997; Bergeron 2001, 2003). It is noteworthy that GD 392B appears to be the first ultracool white dwarf for which a pure hydrogen atmosphere is not inconsistent with the data.

At present there remains a general failure by model predictions to fit the photometric observations of ultracool white dwarfs in detail (Bergeron 2001; Bergeron & Leggett 2002)—a fact exemplified by GD 392B. Another case in point is the SED of WD 0346+246, where both Oppenheimer et al. (2001) and Bergeron (2001) found that a mixed atmosphere model with an extremely low value of $N_{\rm H}/N_{\rm He} \sim 10^{-6}$ to $10^{-9}$ provides a good fit to the data. But because of the unlikelihood and volatility of such a solution, Bergeron (2001) introduced a pseudocontinuum opacity characterized by an ad hoc damping function. Although a good fit with $N_{\rm H}/N_{\rm He} = 0.77$ was achieved when the opacity was added to the models, it is unclear whether this pseudocontinuum source plays a significant physical role in the atmospheres of ultracool white dwarfs. Therefore, it is not yet possible to determine the atmospheric parameters of the coolest degenerates with confidence.

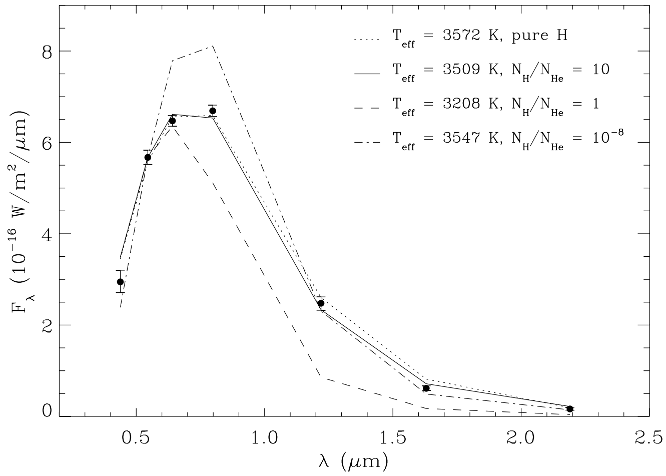


FIG. 9.—Model fits to GD 392B at 57.8 pc with $\log g = 7.0$. Only the $N_{\rm H}/N_{\rm He} = 10$ and pure hydrogen models have any success in reproducing the measurements. Fits at $N_{\rm H}/N_{\rm He} = 10^{-1}$, $10^{-2}$, $10^{-3}$, and $10^{-5}$ have been omitted because they are more discrepant than those shown.

It should be mentioned that with the possible exception of the ultracool white dwarfs in Figure 5, all suspected or confirmed low-mass white dwarfs have hydrogen-rich atmospheres (Bergeron et al. 1992, 2001; Bergeron & Leggett 2002). Hence, a model fit to the photometry of GD 392B with low mass and a mixed H/He atmosphere is inconsistent with these findings.

## 5. DISCUSSION

GD 392B is not the first or even the second ultracool white dwarf for which an apparent large radius is possible or likely. LHS 3250, WD 0346+246, and SDSS 1337+00 all appear to be potentially overluminous (Harris et al. 1999, 2001; Oppenheimer et al. 2001). In fact, the best fits achieved by Oppenheimer et al. (2001) to WD 0346+246 and F351−50 were with $\log g = 6.5$, although for pure hydrogen atmospheres. These solutions are problematic because they predict temperatures below 3000 K and such extreme low gravities. Although unlikely, the present possibility that these ultracool degenerate stars have anomalously low mass cannot be ruled out. White dwarfs with $M < 0.45\ M_\odot$ have relatively large radii and are understood to be the product of close binary evolution, their post–main-sequence lifetimes cut short before helium burning begins (Bergeron et al. 1992; Marsh et al. 1995; Hansen & Phinney 1998). On the other hand, the potential overluminosity of these stars can be explained equally well by binary membership with a white dwarf companion of comparable luminosity. If this is correct, the GD 392 system would then be the second known triple degenerate. In either case, binarity is a strong possibility for most if not all four objects in Figure 5, if the models are correct.

Is it possible that the discovery of these stars represents a luminosity detection bias? This would imply that all known ultracool degenerates were detected because they are relatively bright compared to normal–to–high-gravity single white dwarfs with comparable temperatures. In fact, the faintest white dwarf known, ESO 439−26 (Ruiz et al. 1995), has an extremely high mass ($\log g = 9.0$), a temperature around 4500 K, and $V = 20.5$ mag—just above the detection limit of very large sky surveys such as the SERC/ESO survey in the southern hemisphere and the Palomar survey (POSS II) in the north (Reid et al. 1991). What if ESO 439−26 had $T_{\rm eff} = 3500$ K instead of ∼4500 K? Would it have still been detected? Almost certainly not, since models predict that it would have been too faint at $V = 22.5$ mag and $B-V = 1.0$. A similar calculation was performed for GD 392B, assuming that it is a 3500 K mixed H/He atmosphere degenerate with $\log g = 7.0$ at 57.8 pc. Would it still have been detected were it a higher mass white dwarf with $\log g = 8.5$? Likely not at $V = 21.0$ mag and $B-V \sim 1.2$, which is just beyond the POSS II red plate limit and right at the blue plate limit. It probably would not have been detected in the infrared at $J = 19.2$ mag. Similar conclusions can be drawn for WD 0346+246 at $V = 19.1$ mag but possibly not LHS 3250 at $V = 18.0$ mag. If we similarly push back the magnitude of SDSS 1337+00 to $V = 20.8$ mag, it would still be detectable in the Sloan survey but not on the POSS II plates.

The claim that all known ultracool white dwarfs are overluminous is not being made here. It is simply being stated that *if* the majority of them are indeed brighter than expected because of low gravity or binarity, then all surveys with the exception of Sloan have been biased against detecting average–to–higher mass single white dwarfs at the very bottom of the disk cooling sequence. In fact, one should expect that the oldest white dwarfs—those that spent very little time on the main sequence—would have come from fairly massive progenitors. Furthermore, the initial mass–to–final mass relation for white dwarfs indicates that higher mass main-sequence stars tend to form higher mass degenerates (Weidemann 1987, 1990, 2000; Bragaglia et al. 1995). This implies that the oldest and least luminous white dwarfs should have high masses and small radii and be up to 2.4 mag fainter than a low-mass white dwarf with the same temperature. Hence, there is a possibility that the lowest luminosity disk white dwarfs have yet to be detected.

Of course the other possibility (and, according to Occam's razor, the most likely) is simply a failure of the current models to explain the photometric observations. Also, in this case, the data do not constrain the mass of GD 392, and therefore we do not know distance to the system. Despite the fact that the model predictions fail to reproduce the colors of GD 392B in all but the $\log g = 7.0$ case, it is certainly possible that it has a higher mass. This cannot be ruled out, and future improvements in models may result in the disappearance of the overluminosity issue.

## 6. CONCLUSION

Spectroscopy and photometry confirm a cool DC white dwarf common proper-motion companion to GD 392. It is the first ultracool white dwarf ($T_{\rm eff} < 4000$ K) to be discovered as a companion to another star. Although the primary is a well-studied DB white dwarf, GD 392 does not have a mass estimate nor any kind of reliable parallax. In fact, its helium lines are very weak (Wesemael et al. 1993), and therefore it is not possible to spectroscopically determine its mass. Neither is it possible to photometrically determine its mass because the optical and infrared colors of relatively hot helium atmosphere white dwarfs are insensitive to gravity. Therefore, the distance to the GD 392 system is not well constrained, and the parameters that we derive for GD 392B must come from a range of assumed values for the mass of the primary.

Despite this difficulty, it appears that all model fits fail to reproduce the SED of GD 392B, with the exception of a solution with $\log g = 7.0$, $T_{\rm eff} = 3509$ K, and $N_{\rm H}/N_{\rm He} = 10$ (or similar values with pure hydrogen). It is the only set of parameters for which the model-predicted fluxes fall within 1–1.5 $\sigma$ of all but one photometric data point and that satisfies all constraints. However, the model fit alone is not sufficient to conclude that GD 392B is overluminous. It is possible that current models simply cannot reproduce the observed SED of GD 392B with a normal to higher surface gravity, but perhaps ongoing and future improvements will. On the basis of the data and the models used here, along with the published analyses of similar objects, GD 392B may be an unresolved binary with a companion of comparable luminosity or is itself a low-mass white dwarf. Albeit unlikely, this could also be the case for other known ultracool degenerates. If correct, this may hold interesting consequences for the population of stars at the faint end of the local disk white dwarf luminosity function.

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