THE LOWEST MASS WHITE DWARF

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ABSTRACT

Extremely low mass white dwarfs are very rare objects likely formed in compact binary systems. We present MMT optical spectroscopy of 42 low-mass white dwarf candidates serendipitously discovered in a survey for hypervelocity B-type stars. One of these objects, SDSS J0917+46, has $T_{\text{eff}} = 11.288 \pm 72$ K and log $g = 5.48 \pm 0.03$; with an estimated mass of $0.17 M_\odot$, it is the lowest gravity/mass white dwarf currently known. However, 40 of the low-mass candidates are normal DA white dwarfs with apparently inaccurate SDSS $g$ magnitudes. We revisit the identification of low-mass white dwarf candidates previously found in the SDSS and conclude that four objects have $M < 0.2 M_\odot$. None of these white dwarfs show excess emission from a binary companion, and radial velocity searches will be necessary to constrain the nature of the unseen companions.

Subject headings: stars: low-mass, brown dwarfs — white dwarfs

Online material: color figures

1. INTRODUCTION

The mass distribution of hot DA (hydrogen-rich atmosphere) white dwarfs (WDs) from the Palomar Green Survey peaks at 0.57 $M_\odot$ with a dispersion of 0.19 $M_\odot$ (Liebert et al. 2005). A similar mass distribution is also observed for WDs cooler than 12,000 K (Bergeron et al. 2001). In both cases, separate low-mass and high-mass components to this mass distribution are also observed. The Liebert et al. sample includes WDs with masses as low as 0.32 $M_\odot$, and the mass distribution has a low-mass peak at 0.4 $M_\odot$. These low-mass WDs are understood as He core WDs formed in binary systems. He core WDs can be formed when a companion strips the outer envelope from a post-main-sequence star before the star reaches the tip of the red giant branch and ignites the helium. Low-mass WDs are usually found in close binaries, mostly double degenerate systems (Marsh et al. 1995). The Galaxy is not old enough to produce these WDs through single-star evolution.

Recent discoveries of extremely low mass (ELM; log $g < 7$) WDs in the field and around pulsars show that some of these WDs retain only a small fraction of their progenitor mass and end up with as little mass as 0.2 $M_\odot$. Liebert et al. (2004) were the first to discover an ELM WD in the field (SDSS J1234−02) with $T_{\text{eff}} = 17,470 \pm 750$ K and log $g = 6.38 \pm 0.05$. Eisenstein et al. (2006) increased the number of ELM WD candidates found in the Sloan Digital Sky Survey (SDSS) to 13, including two objects with log $g < 6$. Kawka et al. (2006) added one more object to the list (LP 400-22) with log $g = 6.32 \pm 0.08$. The optical photometry of none of these objects shows an excess, and the nature of the companions to these objects is not known.

The existence of ELM WDs around pulsars suggests that neutron star companions may be responsible for creating such low-mass WDs. PSR J0437−4715, J0751+1807, J1012+5307, J1713+0747, B1855+09, and J1909−3744 are pulsars in circular pulsar-He WD binary systems with orbital periods of ~0.2−100 days (Nice et al. 2005). The properties of the pulsars in these systems differ markedly from those of typical isolated pulsars, showing more rapid spin periods and smaller inferred magnetic fields. They also tend to have masses greater than the canonical value of 1.35 $M_\odot$. The relatively high masses of pulsars in these systems presumably result from extended mass accretion during the late stages of their evolution (Nice et al. 2005). At the cessation of mass transfer, the neutron star turns on as a millisecond radio pulsar and the companion is left as a helium core WD (van Kerkwijk et al. 2000).

Optical spectroscopy of two of the low-mass WD companions to pulsars is available in the literature; van Kerkwijk et al. (1996) found a best-fit solution of $T_{\text{eff}} = 8550 \pm 25$ K and log $g = 6.75 \pm 0.07$ for the companion to PSR J1012+5307, whereas Bassa et al. (2006) measured $T_{\text{eff}} = 10,090 \pm 150$ K and log $g = 6.44 \pm 0.20$ for the companion to PSR J1911−5958A. In addition, Heber et al. (2003) found a subluminous B (sdB) star, HD 188112, with $T_{\text{eff}} = 21,500 \pm 500$ K and log $g = 5.66 \pm 0.05$ and suggested that it is the progenitor of a helium core WD. HD 188112 is in a binary system with an $M > 0.73 M_\odot$ compact object, a WD or a neutron star.

Recently, Brown et al. (2006) performed a search for hypervelocity stars in the SDSS Fourth Data Release. They used the SDSS photometry to select faint B star candidates in a survey area of ~3000 deg$^2$. They obtained follow-up spectroscopy of 247 candidates with the Blue Channel Spectrograph on the 6.5 m MMT telescope, 44 of which turned out to be WDs. The SDSS colors for ELM WDs fall into the same region as their selection region for B-type stars; thus, they identify all of these WDs as potential low-mass WDs with log $g < 7$. Figure 1 shows $u−g$ versus $g−r$ color-color diagram of the low-mass WD candidates from Brown et al. (2006, circles) and Eisenstein et al. (2006; triangles). Our synthetic photometry of WD model atmospheres with log $g = 5, 6, 7$, and 8 (Finley et al. 1997) are shown as solid lines. B-type stars found in Brown et al.’s survey are shown as crosses. It is clear from this figure that all of the WDs found by Brown et al. (2006) lie to the right of the log $g = 7$ line and are candidate low-mass WDs. In addition, one of these WDs has colors similar to the lowest mass WD candidate identified by Eisenstein et al. (2006).
same set of WD model atmospheres. We have chosen to smooth the spectra to \( R = 2500 \). This also increases slightly the signal-to-noise ratio (S/N) of the observed spectra. We use the radial velocities measured by Brown et al. (2006) to correct the spectra to the rest frame. After smoothing the spectra by convolution with a Gaussian kernel of the appropriate width, and resampling with 4 points per resolution element (constant step in log \( \lambda \)), the spectra were normalized using two different procedures: (1) determining the continuum by iteratively fitting a polynomial (six iterations), then dividing by the fit; and (2) dividing each spectrum by its median value. In the first case, the shape of the spectral energy distribution (SED) is effectively removed, losing valuable information but avoiding systematic errors in the flux calibration and the effects of reddening. We note that we apply the same procedures to both the observed and model spectra in all cases.

The grid of WD model atmospheres covers effective temperatures from 6000 to 30,000 K in steps of 1000 K, and surface gravities from \( \log g = 5.0 \) to 9.0 in steps of 0.25 dex. The best-fit parameters are determined for each star by searching for the minimum \( \chi^2 \) in the range covered by the spectrum using the Nelder-Mead algorithm (Nelder & Mead 1965), performing quadratic Bezier interpolation of the spectra in both \( T_{\text{eff}} \) and \( \log g \) (Allende Prieto 2004). In the case of full continuum normalization (case 1), we only fit the Balmer line profiles, whereas we fit the entire spectrum in case 2. The derived error bars for the parameters are simply the square roots of the diagonal elements of the covariance matrix (Press et al. 1986).

If the analysis is carried out at different resolving powers, the results change slightly for case 1, where we fit the Balmer lines. We have repeated our fits with \( R \) changing from 2500 to 200, and found that the drift can be approximately matched with a 1/2 law.

We find that a reduction of resolving power from infinity to 2500 causes \( T_{\text{eff}} \) to be overestimated by 1% and \( \log g \) by 0.04 dex. Since our spectra are mostly composed of strong Balmer lines, it is hard to determine the continuum in the blue part of the spectrum. In addition, the removal of the continuum sacrifices useful information and, in the presence of noise, introduces degeneracy—a decrease in \( T_{\text{eff}} \) can be compensated by an increase in \( \log g \), and multiple minima are apparent, although one is usually significantly deeper than the other.

In case 2, where we fit the entire spectrum, the parameters that we derive are independent of the resolution that we use down to \( R \geq 200 \); therefore, these results are more robust than those derived from the normalized spectra. In addition, the degeneracy problem is resolved with the additional information contained in the continuum shape. A comparison of our fits for cases 1 and 2 shows that on average our temperature and \( \log g \) estimates differ by \( \sim 800 \) K and 0.07 dex, respectively. Figure 2 shows the \( \log g \) for our spectral fits using the line profiles from the continuum-corrected spectra (case 1) versus using the spectra without any continuum correction (case 2). This figure suggests that our gravity estimates are robust. With the exception of four objects for which flux calibration errors are apparent in the observed spectra (Cand 17, 20, 124, and 192), the quality of our fits (minimum \( \chi^2 \)) is always better when the continuum shape is not removed.

We prefer the \( T_{\text{eff}} \) and \( \log g \) from our best-fit case 2 solutions. Our fits to the original spectra contain more information than
WD candidates identified by Brown et al. (2006). Figure 4 shows that the majority of the objects in our sample have log $g$ and log $T_{\text{eff}}$ consistent with the derived temperature and gravity. Figure 4 completely at odds with the SDSS photometry, and we come back to this point in § 3. More importantly, the case of Cand 171 is the only one of our low-mass WD candidates identified by Brown et al. (2006).

Repeat observations of one of our targets over several nights shows that our real errors are larger than our internal error estimates (in Table 1). Analyzing nine different spectra of the same object, we find that the average internal errors in $T_{\text{eff}}$, log $g$, and $\chi^2$ are $0.34$, $0.36$, and $0.20$ dex, respectively, while the empirical estimates indicate $0.36$, $0.38$, and $0.20$ dex. The real error bars (set by systematic errors in our analysis) are more like $5\%$ in $T_{\text{eff}}$ and $0.08$ dex in log $g$.

### 2.2 Results

A glance at our best-fit $T_{\text{eff}}$ and log $g$-values given in Table 1 shows that the majority of the objects in our sample have log $g > 7$ and therefore, by our definition, are not ELM WDs. This is completely at odds with the SDSS photometry, and we come back to this point in § 3. More importantly, the case of Cand 171 (J0917+46) deserves particular attention.

The WD J0917+46 has $T_{\text{eff}} = 11.288 \pm 72$ K and log $g = 5.48 \pm 0.03$. The extremely low log $g$ is identical to the log $g$ estimate of the previous lowest mass WD candidate, J2049+00 (Eisenstein et al. 2006). However, Eisenstein et al. find evidence of multiple minima, and the available photometry for J2049+00 is inconsistent with this solution (see § 3). In the case of our lowest-gravity object, J0917+46, both the spectrum and the SED are consistent with the derived temperature and gravity. Figure 4 presents the $\chi^2$ distribution of our fits to the J0917+46 spectrum, which shows no evidence of any other minima in the explored parameter space.

In order to demonstrate that our fit for J0917+46 is reliable, we present our fits to the flux-normalized line profiles in Figure 5. These fits follow Liebert et al. (2004), Kawka et al. (2006), and Bassa et al. (2006), who correct their spectra of
low-mass WDs and fit just the Balmer lines. We note that the \( \chi^2 \) (per degree of freedom) is slightly higher in this case (2.08) compared to the \( \chi^2 \) derived from fitting the entire spectrum (1.45). However, the best-fit solution, \( T_{\text{eff}} = 10,760 \pm 99 \) K and \( \log g = 5.46 \pm 0.04 \), nicely agrees with our solution presented in Figure 3 and Table 1. Thus, J0917+46 is the lowest gravity WD currently known.

3. UNDERSTANDING THE SDSS LOW-MASS WHITE DWARF SAMPLE

The discrepancy between the SDSS photometry and our spectroscopic analysis initially puzzled us. Even though SDSS photometry of all of our candidates was consistent with their ELM WD classification, only J0917+46 and J1053+52 turned out to have \( \log g < 7 \). What went wrong? We begin by comparing the SEDs of our low-mass candidates with the SDSS broadband photometry. We then reanalyze the spectra of other low-mass WD candidates previously found in SDSS.

3.1. Discrepant SDSS Photometry

We have examined the SEDs of our candidates obtained from the SDSS photometry and compared them to our best-fit solutions from spectroscopy. We have applied the following AB...
corrections to the observed SDSS magnitudes: \(u - 0.04\), \(i + 0.015\), \(z + 0.03\), and no corrections in \(g\) and \(r\) (see Eisenstein et al. 2006). The SDSS database gives the total interstellar absorption and reddening along the line of sight for each star, determined from the dust emission maps of Schlegel et al. (1998). Since all of our targets are at relatively high Galactic latitudes, the total absorption and reddening are small; the median total absorption \(A_g\) is 0.11, and the median total reddening \(E(g-i)\) is 0.05. Therefore, the errors in the reddening corrections have little effect on our analysis.

We have calculated the predicted fluxes from our best-fit model atmosphere by integrating over the SDSS filter bandpasses. Without knowing the radii and distances to the WDs, we have used a \(\chi^2\) minimization technique to match the predicted fluxes with the observed fluxes. The value of \(\chi^2\) is taken as the sum over all bandpasses of the difference squared between the predicted and observed fluxes, properly weighted by the corresponding observational uncertainties.

Figure 6 shows the SEDs of four of the objects observed at the MMT plus the lowest mass WD candidate identified by Eisenstein et al. (2006). The dereddened SDSS photometry and the fluxes predicted for the parameters derived from our spectroscopic analysis are shown as error bars and circles, respectively. A comparison of the photometry and our best-fit solutions shows that the SDSS \(g\)-band photometry is systematically discrepant. For example, our best-fit solution for J0745+18 and J1529+33 (top two panels) reproduce \(u, r, i, \) and \(z\) photometry reasonably well. However, the SDSS \(g\) magnitudes are 20\%–30\% brighter than expected for these two objects (as well as many other candidates in the MMT sample). In order to check if the discrepancy is caused by our small reddening correction, we have also compared the predicted fluxes to the observed (not dereddened) SDSS photometry and found the same discrepancy in the \(g\) band. Brighter \(g\)-band magnitudes cause the objects to have more positive \(u-g\) colors and more negative \(g-r\) colors that are consistent with low-mass WDs. This suggests that SDSS photometry cannot be used by itself to identify ELM WDs.

We note that the \(g\)-band magnitude for the previous lowest mass WD candidate, J2049+00 (Eisenstein et al. 2006), may also be suspect. The bottom panel of Figure 6 shows that the SED of J2049+00 is discrepant with its \(g\)-band magnitude, and thus, we revisit its identification as an ELM WD.
3.2. The SDSS Sample

We now bring together the low-mass WD candidates previously found in SDSS. Kleinman et al. (2004) identified 2561 WDs, including several WDs with unusually low surface gravities, in the SDSS DR1 spectroscopy data. Liebert et al. (2004) performed model atmosphere analysis of two of these unusual WDs and found them to be ELM WDs. They have also found several other fainter low-mass WD candidates with noisy spectra. Eisenstein et al. (2006) study WDs across the entire SDSS DR4 and find 13 ELM WD candidates, including the ELM WD candidates identified in the SDSS DR1.

Eisenstein et al. (2006) use the same model atmospheres as we do; however, the log $g$ sampling of their grid is coarser than ours (0.50 dex sampling compared to our 0.25 dex sampling). The procedure employed by Eisenstein et al. (see Kleinman et al. 2004) makes use of quadratic interpolation in $\chi^2$ to find the location of the minimum with subpixel resolution, while our method performs quadratic interpolation in the model fluxes, which is more accurate. In addition to using the SDSS spectra from 3900 to 6800 Å, Eisenstein et al. also include SDSS colors in their fits. Using photometry can help constrain the temperature in the spectroscopic analysis of stars with reliable photometry. However, as we have demonstrated in §2, it may not be ideal to analyze the outliers in color-color diagrams for which the SDSS photometry may be inaccurate. The lowest mass WD candidate found by Eisenstein et al. (2006) is an unfortunate example of this.

In order to confirm the ELM WD candidates found by Eisenstein et al. (2006), we use the same procedures for our MMT spectra to fit the SDSS sample. The SDSS spectra are noisier compared to our MMT data, and the derived parameters are therefore less reliable. We smooth the spectra to $R = 1000$ in order to increase the S/N, and the models are also degraded to the same resolution. We fit WD model atmospheres to the SDSS spectra in the spectral range 3800–4500 Å. The SDSS spectra are usually noisier in the red, and even including H$\beta$ does not change our results significantly. Our temperature estimates differ significantly from the Eisenstein et al. (2006) estimates only for two WDs: J0822+27 and J1630+42. Using only spectroscopy led to best-fit solutions significantly different from the photometric estimates, and including the $g$–$r$ colors in our fits solved the problem for these two stars. The spectroscopic and photometric solutions agreed well for the rest of the SDSS sample. Figure 7 shows our best-fit models (solid lines) to the observed SDSS spectra (jagged lines) of low-mass WD candidates. Table 2 presents $T_{\text{eff}}$ and log $g$
estimates from our study, and those from Liebert et al. (2004) and Eisenstein et al. (2006).

Comparisons of temperatures and surface gravities from our analysis, Liebert et al. (2004; squares), and Eisenstein et al. (2006; circles) are presented in Figure 8. Open symbols represent the objects with low S/N SDSS spectroscopy. This figure shows that our results for the two ELM WDs analyzed by Liebert et al. (2004) are consistent with their analysis. Our temperature estimates differ from Eisenstein et al. (2006) results by 141 ± 150 K, and our surface gravity estimates are different by 0.13 ± 0.16 dex (excluding the two lowest gravity candidates). We note that one object, J1053+52, is common to both the MMT and SDSS samples. Our fits to the MMT spectrum of this object yield $T_{\text{eff}} = 15.882 \pm 41$ K and $\log g = 6.40 \pm 0.01$, and the SDSS spectrum yields $T_{\text{eff}} = 18.328 \pm 235$ K and $\log g = 6.40 \pm 0.05$. The nature of this object as an ELM WD is confirmed by our analysis.

One major difference between this work and Eisenstein et al. (2006) is that we find a best-fit solution of $\log g < 5$ for their lowest mass WD candidate, J2049+00. We have repeated our fits for this star by fitting the flux calibrated line profiles and also fitting the entire SDSS spectrum, and in both cases we find that the best-fit solution is exactly our lowest gravity model ($\log g = 5$). Eisenstein et al. (2006) find evidence for multiple minima in their fits for this star, and they conclude that the available photometry is more consistent with a lower gravity ($\log g < 5$) solution. Here we demonstrate that the SDSS spectrum of J2049+00 is also consistent with a lower gravity ($\log g < 5$) solution, and therefore, it is not a WD. We performed the Clewley et al. (2002) line shape test for the classification of halo A-type stars, but the results are ambiguous. The Hγ profile is marginally consistent with the star being a blue horizontal branch (BHB) star, but the Hδ profile is inconsistent with a BHB star. Based on H line indices we determine the spectral type of J2049+00 to be A2 with an uncertainty of ±1.2 subtypes. If J2049+00 is an A star with $M_V \sim 1$, then it is located at ~36 kpc. The lack of a significant proper motion in the USNO-B catalog is consistent with it being a distant A star.

Our fits also indicate that J0849+04 (with S/N < 10 spectroscopy), Eisenstein et al.’s (2006) second lowest mass WD candidate with $T_{\text{eff}} = 9962$ K and $\log g = 5.93 \pm 0.15$, is better fit with a $T_{\text{eff}} = 12,000 \pm 208$ K and $\log g = 7.34 \pm 0.07$ model atmosphere. Our fits to the Balmer lines (continuum-corrected spectrum) also result in a best-fit solution of $T_{\text{eff}} = 12,397 \pm 91$ K and $\log g = 7.21 \pm 0.05$. Both of these fits suggest that J0849+04 is a low-mass WD, but not an ELM WD.
Fig. 7.—Spectral fits (solid lines) to the SDSS spectra (jagged lines) of low-mass WD candidates identified by Eisenstein et al. (2006). [See the electronic edition of the Journal for a color version of this figure.]

TABLE 2

| Object            | \(T_{\text{eff}}\) (K; this work) | \(\log g\) (this work) | \(T_{\text{eff}}\) (K; SDSS) | \(\log g\) (SDSS) | S/N* |
|-------------------|----------------------------------|------------------------|----------------------------|------------------|------|
| J0022+00           | 19562 ± 153                      | 7.12 ± 0.05            | 17355 ± 394                | 6.95 ± 0.11      | 9.6  |
| J0022–10          | 18397 ± 299                      | 6.82 ± 0.07            | 19444 ± 758                | 6.76 ± 0.16      | 7.0  |
| J0822+27          | 8937 ± 48                        | 7.21 ± 0.04            | 8777 ± 40                  | 6.78 ± 0.11      | 20.3 |
| J0849+04          | 12000 ± 208                      | 7.34 ± 0.07            | 9962 ± 165                 | 5.93 ± 0.15      | 8.5  |
| J1053+52          | 18328 ± 235                      | 6.40 ± 0.05            | 15399 ± 400                | 6.28 ± 0.11      | 10.7 |
| J1056+65          | 19000 ± 151                      | 7.03 ± 0.05            | 20112 ± 634                | 6.94 ± 0.12      | 9.4  |
| J1056+65b         |                                  |                        | 21910 ± 1900               | 7.07 ± 0.10      |      |
| J1234–02          | 16897 ± 78                        | 6.49 ± 0.02            | 17114 ± 227                | 6.30 ± 0.05      | 21.2 |
| J1234–02b         |                                  |                        | 17470 ± 750                | 6.38 ± 0.05      |      |
| J1426+01          | 15869 ± 112                      | 7.02 ± 0.03            | 16311 ± 359                | 6.92 ± 0.09      | 10.7 |
| J1436+50          | 18339 ± 110                      | 6.59 ± 0.02            | 16993 ± 229                | 6.58 ± 0.06      | 17.6 |
| J1625+36          | 23000 ± 435                      | 6.01 ± 0.07            | 24913 ± 936                | 6.20 ± 0.15      | 8.7  |
| J1630+42          | 14183 ± 942                      | 7.08 ± 0.07            | 14854 ± 359                | 6.89 ± 0.13      | 7.0  |
| J2049+00          | 8581 ± 31                        | 5.00 ± 0.12            | 8660 ± 144                 | 5.48 ± 0.10      | 12.9 |
| J2252–00          | 19114 ± 99                       | 7.12 ± 0.03            | 20479 ± 433                | 6.85 ± 0.08      | 13.5 |

*S/N of the SDSS spectra in the g band.

**T_{\text{eff}}** and \(\log g\) fits by Liebert et al. (2004).
The rest of the objects in the Eisenstein et al. (2006) low-mass WD sample seem to have surface gravities in the range \( g = 6-7.3 \), and hence our analysis supports their classification as low-mass WDs. However, the SDSS spectroscopy for the majority of them is very noisy, especially in the blue, and a better understanding of these objects must await higher S/N spectroscopy.

4. DISCUSSION

Our spectroscopic analysis of the low-mass WD candidates in the SDSS shows that J0917+46 has \( T_{\text{eff}} = 11.288 \pm 72 \text{ K} \) and \( g = 5.48 \pm 0.03 \), and it is the lowest surface gravity WD currently known. We find one other ELM WD in our MMT sample, J1053+52. The remaining 40 candidates observed at the MMT are normal DA WDs with apparently inaccurate SDSS \( g \) magnitudes. We also confirm the low surface gravities of the ELM WD candidates identified by Eisenstein et al. (2006), with the exception of their lowest mass WD candidate.

Figure 9 shows the effective temperatures and surface gravities for the MMT (filled circles) and SDSS (triangles) samples plus the previously identified ELM WDs in the literature (open circles). Solid lines show the constant mass tracks for low-mass WDs\(^6\) from Althaus et al. (2001; labeled in \( M_{\odot} \), on the right side of the figure), and the tracks for zero-age main sequence (ZAMS) and horizontal branch stars. The zero-age BHB marks the location of the star at the start of the core-helium burning phase. Stars evolve upward to lower log \( g \)-values as the He burning proceeds.

Figure 9 shows that the majority of the WDs found by Brown et al. (2006) have \( M \sim 0.5 \, M_{\odot} \). Only two objects, J0917+46 and J1053+52, have \( M < 0.2 \, M_{\odot} \). All of the low-mass WD candidates identified by Eisenstein et al. (2006), except J2049+00, have \( M \leq 0.36 \, M_{\odot} \); therefore, they should have formed in binary systems. None of the stars in the MMT sample or the SDSS sample show excesses in their SDSS photometry; therefore, the companions are likely to be compact objects. We have two separate spectra for J1053+52. We have measured a radial velocity of \( -53 \pm 18 \text{ km s}^{-1} \) from the MMT spectrum obtained on 2006 February 24, and a velocity of \( 11 \pm 38 \text{ km s}^{-1} \) from the SDSS observations obtained on 2003 January 10. The observed radial velocity change may be real; however, more accurate and time-resolved spectroscopic observations of this object, as well as all the other ELM WDs in our study, are required to constrain the mass of the unseen companion.

Figure 9 demonstrates that J0917+46 is an ELM WD and not a BHB or a main-sequence star. Its temperature and surface gravity imply an absolute magnitude of \( M_V \sim 6.9 \) (Althaus et al. 2001) and an age of 470 Myr. This luminosity places it at a distance of 2.6 kpc. At a Galactic latitude of +44°, it is located at 1.8 kpc above the plane. J0917+46 has a proper-motion measurement of 0 mas yr\(^{-1}\) in the USNO-B catalog, which is consistent with a distant object. Our radial velocity measurement of \( 165 \pm 12 \text{ km s}^{-1} \) from the MMT spectroscopy corresponds to \( U = -108, V = 25, \) and \( W = 122 \text{ km s}^{-1} \) (helio-centric), consistent with a thick disk or halo WD (Chiba & Beers 2000). If the observed radial velocity is due to the orbital motion of the star, then it would be more consistent with a thick disk WD.

Low-mass WDs can be produced in low-mass X-ray binaries (LMXBs; WD–neutron star binaries) or in a common-envelope
phase with other companion stars. About 90% of the known LMXBs are located in the Galactic plane ($b \leq 20^\circ$; Ritter & Kolb 2003). If J0917+46 had a neutron star companion, we would need an explanation for its peculiar location above the Galactic plane. The unusually high velocity of another extremely low mass WD, LP 400-22 (Kawka et al. 2006), indicates that LP 400-22 may have been released from its close binary. A similar scenario may explain the peculiar location of J0917+46.

Althaus et al. (2001) models predict J0917+46 to have $M \sim 0.17 M_\odot$, $L \sim 0.2 L_\odot$, and $R \sim 0.12 R_\odot$, about 9 times bigger than a typical $0.6 M_\odot$ WD. Other calculations and mass radius relations should give similar results, within a few $0.01 M_\odot$ (see Bassa et al. 2006). A close examination of the spectrum of this object reveals a Ca K line (Cand 171 in Fig. 3). The Ca K line has an equivalent width of 0.35 Å and a radial velocity measurement of 164 km s$^{-1}$; it is photospheric. The equivalent width of the Ca line is similar to the DAZs observed by Zuckerman et al. (2003) and Koester et al. (2005), and corresponds to an abundance of log (Ca/H) $= -5.89$ (nearly solar). J0917+46 has more Ca than many of the DAZs with circumstellar debris disks, and requires an external source for the observed metals (Kilic & Redfield 2007). The star is located far above the Galactic plane where accretion from the interstellar medium is unlikely (Dupuis et al. 1993). The nature of the possible companion star needs to be determined before the Ca abundance can be explained.

Extremely low mass WDs seem to be rare. Eisenstein et al. (2006) found only 13 candidates in the SDSS DR4 area (4783 deg$^{-2}$). We have identified two ELM WDs (one in common with their analysis) in 3000 deg$^{-2}$. However, our search was limited to $-0.39 < g-r < -0.27$ (and therefore to $T_{\text{eff}} > 11,000$ K for log $g < 6$ WDs). Eisenstein et al. (2006) made an initial color cut to select their WD candidates for spectroscopic analysis. Their initial color cut included the $u-g$ versus $g-r$ region where we expect to find log $g \geq 5$ WDs; however, they did not find any WD candidates with $M < 0.17 M_\odot$.

Detailed calculations of the evolution of 1–3 $M_\odot$ stars in close binary systems with neutron stars show that the final mass of the He core WD produced in the process can be as low as 0.02 $M_\odot$ (Benvenuto & De Vito 2005). Ergma et al. (1998) argued that if the initial orbital period of a 1 $M_\odot$ Population II object in a binary system with a neutron star is less than 0.95 days, the orbital evolution of the system would proceed toward very short orbital periods, and these systems would end their evolution as ultracompact LMXBs with a WD secondary mass of $\leq 0.1 M_\odot$ (e.g., 4U 1820–30 is an LMXB with an orbital period of 11 minutes and an estimated secondary mass of $M \sim 0.06–0.08 M_\odot$; Stella et al. 1987; Rappaport et al. 1987). They also argued that if the initial orbital period of the system is between 0.95 and 1.50 days (the upper limit is the bifurcation orbital period), the systems would evolve toward shorter orbital periods and LMXBs with orbital periods of $\geq 10$ hr will be formed. Ergma et al. (1998) found that the lowest mass WDs in such systems would be 0.15–0.16 and 0.17 $M_\odot$ for Population I and II stars, respectively. These low-mass limits also seem consistent with the analysis of Benvenuto & De Vito (2005).

Binary millisecond pulsar systems with low-mass WD secondaries are thought to be the descendants of the LMXBs. All of the currently known WDs in the field and around the millisecond pulsars have masses larger than 0.17 $M_\odot$. The masses of some of these WDs have been determined from the Shapiro (1964) delay of the pulsar signal in the gravitational field of the companion WD (Lo¨hmer et al. 2005). This delay is linearly proportional to the mass of the companion, and therefore, the nondetection of $M < 0.17 M_\odot$ WDs around pulsars may be an observational bias. A more targeted search for these objects may find WDs with smaller masses; however, identifying these low-mass objects as low-mass WDs may be challenging. On the other hand, if the binary formation models of low-mass He core WDs around neutron stars are correct, we would expect to find lower mass WDs only in ultracompact LMXBs and their descendants.

5. CONCLUSIONS

We have performed spectroscopic analysis of the low-mass WD candidates found in the SDSS. We have shown that SDSS J0917+46 is the lowest mass WD currently known with $M \sim 0.17 M_\odot$. In addition, there are three more WDs in the SDSS with masses smaller than 0.2 $M_\odot$. These WDs presumably have unseen companions. A radial velocity search for these unseen companions will be necessary to constrain their masses and the evolutionary scenarios for the formation of extremely low mass WDs. So far, both of the spectroscopically confirmed $\sim 0.2 M_\odot$ WDs with known companions (PSR J1123+5307 and J1911–5958A) are in 14.5–20 hr orbits around neutron star companions (van Kerkwijk et al. 1996; Bassa et al. 2006). If J0917+46 is in a binary system with a neutron star, we expect a similar orbital period.

The search for radio pulsars around eight low-mass WDs by van Leeuwen et al. (2006) did not find any pulsar companions, and they concluded that the fraction of low-mass He core WDs with neutron star companions is less than 18% ± 5%. However, their sample included only one WD with $M \sim 0.2 M_\odot$ (SDSS J1234–02). Liebert et al. (2004) argued that if the binary separation is appropriate, it is possible to create an extremely low mass WD in a WD–WD binary as well. Time-resolved radial velocity measurements will be necessary to differentiate between these two formation scenarios. Excluding the ultrashort period LMXBs, the models for the formation of low-mass helium WDs in millisecond pulsar binary systems predict the lowest mass WDs to have $M \sim 0.17 M_\odot$. J0917+46 may be an example of the lowest mass WDs produced in such systems.

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