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VISITORS FROM THE HALO: 11 Gyr OLD WHITE DWARFS IN THE SOLAR NEIGHBORHOOD[*]

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ABSTRACT

We report the discovery of three nearby old halo white dwarf (WD) candidates in the Sloan Digital Sky Survey (SDSS), including two stars in a common proper motion binary system. These candidates are selected from our 2800 deg^2 proper motion survey on the Bok and U.S. Naval Observatory Flagstaff Station 1.3 m telescopes, and they display proper motions of 0″.4–0″.5 yr^{-1}. Follow-up MMT spectroscopy and near-infrared photometry demonstrate that all three objects are hydrogen-dominated atmosphere WDs with $T_{\rm eff} \approx 3700$–4100 K. For average mass WDs, these temperature estimates correspond to cooling ages of 9–10 Gyr, distances of 70–80 pc, and tangential velocities of 140–200 km s^{-1}. Based on the UVW space velocities, we conclude that they most likely belong to the halo. Furthermore, the combined main-sequence and WD cooling ages are 10–11 Gyr. Along with SDSS J1102+4113, they are the oldest field WDs currently known. These three stars represent only a small fraction of the halo WD candidates in our proper motion survey, and they demonstrate that deep imaging surveys like the Pan-STARRS and Large Synoptic Survey Telescope should find many old thick disk and halo WDs that can be used to constrain the age of the Galactic thick disk and halo.

Key words: stars: atmospheres – stars: evolution – white dwarfs

Online-only material: color figures

1. INTRODUCTION

White dwarf (WD) cosmochronology provides an independent and accurate age dating method for different Galactic populations (Winget et al. 1987; Liebert et al. 1988). Using 43 cool WDs in the solar neighborhood, Leggett et al. (1998) derived a disk age of 8 ± 1.5 Gyr. Kilic et al. (2006) and Harris et al. (2006) significantly improved the field WD sample by using Sloan Digital Sky Survey (SDSS) and USNO-B astrometry to select high proper motion candidates. However, their survey suffered from the magnitude limit of the Palomar Observatory Sky Survey plates, and they were unable to find many thick disk or halo WD candidates.

Substantial investment of the *Hubble Space Telescope* time on two globular clusters, M4 and NGC 6397, revealed clean WD cooling sequences. Hansen et al. (2004, 2007) and Bedin et al. (2009) use these data to derive cooling ages of ≈12 Gyr for the two clusters. The coolest WDs in these clusters are about 650 $\pm$ 230 K cooler than the coolest WDs in the disk (Kowalski 2007). These studies demonstrate that the Galactic halo is older than the disk by ≥2 Gyr (Hansen et al. 2002; Fontaine et al. 2001; Kowalski 2007). Even though the WDs in globular clusters provide reliable age estimates, these clusters may not represent the full age range of the Galactic halo. The required exposure times to reach the WD terminus in globular clusters limit these studies to the nearest few clusters. In addition, only two-filter (*V* and *I*) photometry is used to model the absolute magnitude and color distribution of the oldest WDs to derive ages. The far closer and brighter WDs of the local halo field are an enticing alternative as well as complementary targets, with the additional potential to constrain the age range of the Galactic halo. Accurate ages for field WDs can be obtained through optical and near-infrared photometry and trigonometric parallax measurements. Nearby WDs can also be used to understand the model uncertainties and put the Globular cluster ages on a more secure footing.

The quest for field halo WDs has been hampered by the lack of proper motion surveys that go deep enough to find the cool halo WDs. The initial claims for a significant population of halo WDs in the field (Oppenheimer et al. 2001a) and in the Hubble Deep Field (Ibata et al. 2000; Méndez & Minniti 2000) were later rejected by detailed model atmosphere analysis (see Bergeron et al. 2005, and references therein) and additional proper motion measurements (Kilic et al. 2004, 2005). To date, the coolest known probable halo WDs are WD 0346+246 (Hambly et al. 1997; Bergeron 2001) and SDSS J1102+4113, with $T_{\rm eff} \approx 3800$ K (Hall et al. 2008). There are also about a dozen ultracool WDs detected in the SDSS (Gates et al. 2004; Harris et al. 2008) that may be thick disk or halo WDs, but current WD atmosphere models have problems in reproducing their intriguing spectral energy distributions (SEDs). Therefore, their temperatures and ages remain uncertain.

Here, we report the identification of three old halo WD candidates discovered as part of our Bok and USNO proper motion survey. The details of this survey and our follow-up observations are discussed in Section 2, whereas our model fits and analysis are discussed in Section 3.

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2. OBSERVATIONS

In 2006 January, we started an *r*-band second-epoch astrometry survey with the Steward Observatory Bok 90 inch telescope with its 90Prime camera (Williams et al. 2001; Liebert et al. 2007). The 90Prime provides a field of view of 1.0 deg^2 with 0″.45 pixel^{-1} resolution. Since 2009 additional observations have been obtained with the U.S. Naval Observatory Flagstaff Station 1.3 m telescope using the CCD Mosaic Camera (1.4 deg^2 field of view with 0″.6 pixel^{-1} resolution). We limited our program to the SDSS Data Release 3 footprint in order to have a relatively long time baseline between our program and the SDSS observations. We obtain proper motion errors of roughly 20 mas yr^{-1} at $r = 21$ mag ($g = 22$ mag for cool WDs).

We select candidates for follow-up spectroscopy based on our proper motion measurements and the photometric colors. We further limit our sample to objects with high proper motion and relatively red colors in order to find the elusive thick disk and halo WDs. We started the follow-up optical spectroscopy of candidate halo WDs at the 6.5 m MMT equipped with the Blue Channel Spectrograph in 2009 June. Here, we present low-resolution spectroscopy of three halo WD candidates with $g - i = 1.5$–1.75 mag. These observations were performed on UT 2009 June 19–21. Our targets are SDSS J213730.87+105041.6, J214538.16+110626.6, and J214538.60+110619.0 (hereafter J2137+1050, J2145+1106N, and J2145+1106S, respectively). We used a 1″.25 slit and the 500 line mm^{-1} grating in first order to obtain spectra with a wavelength coverage of 3660–6800 Å and a resolving power of $R = 1200$. The *g*-band magnitudes of our targets range from 21.0 to 21.8 mag, and the exposure times range from 60 to 100 minutes. We obtained all spectra at the parallactic angle and acquired He–Ar–Ne comparison lamp exposures for wavelength calibration. We use the observations of the spectrophotometric standard star G24-9, which is also a cool WD, for flux calibration.

In addition, we obtained *J*- and *H*-band imaging observations of our targets using the MMT and Magellan Infrared Spectrograph (MMIRS; McLeod et al. 2004) on the MMT on UT 2009 September 2 and 4. The FWHM of the images ranges from 0″.8 to 1″.3. We use a 1″.0 or 1″.4 aperture for photometry. The 6′.8 × 6′.8 field of view of MMIRS enables us to use 20–50 nearby Two Micron All Sky Survey (2MASS) stars to calibrate the photometry. The optical and near-infrared photometry of our targets, as well as proper motions, are presented in Table 1. The optical photometry is in the AB system and the *JH* photometry is in the 2MASS (Vega) system. We use the corrections given in Eisenstein et al. (2006) to convert the SDSS photometry to the AB system. Two of our targets, J2145+1106N and S (N for north and S for south), are separated by 10″ and they have proper motions consistent within the errors. Hence, they are in a common proper motion binary system.

Out of the three targets, only J2145+1106S is detected in the USNO-B catalog, and it has a proper motion of $\mu_{\rm R.A.} = 181.3 \pm 5.2$ mas yr^{-1} and $\mu_{\rm decl.} = -367.7 \pm 5.2$ mas yr^{-1} (Munn et al. 2004). These proper motion measurements are consistent with our measurements within the errors, and they demonstrate that our proper motion measurements are reliable.

3. MODEL ATMOSPHERE ANALYSIS

Our MMT spectroscopy shows that all three targets have featureless spectra; they are cool DC WDs. Below 5000 K, Hα disappears in cool WD spectra. However, hydrogen can still show its presence through the red wing of Lyα absorption

Table 1
New Halo WD Candidates

Parameter	J2137+1050	J2145+1106N	J2145+1106S
R.A.[a]	21:37:30.87	21:45:38.16	21:45:38.60
Decl.[a]	+10:50:41.6	+11:06:26.6	+11:06:19.0
μ_α (mas yr^{-1})	−228.9	+191.9	+185.9
μ_δ (mas yr^{-1})	−473.6	−366.9	−367.7
u	23.31 ± 0.69	23.74 ± 0.91	23.45 ± 0.75
g	21.77 ± 0.06	21.45 ± 0.05	21.00 ± 0.03
r	20.51 ± 0.03	20.27 ± 0.03	19.93 ± 0.02
i	20.02 ± 0.03	19.75 ± 0.02	19.49 ± 0.02
z	19.73 ± 0.08	19.68 ± 0.07	19.38 ± 0.06
J	19.21 ± 0.10	18.87 ± 0.07	18.54 ± 0.06
H	19.25 ± 0.18	19.00 ± 0.10	18.31 ± 0.06
$T_{\rm eff}$ (K)	3780	3730	4110
Age[b] (Gyr)	9.6	9.7	8.7
Distance[b] (pc)	78	69	70
$V_{\rm tan}$ (km s^{-1})	195	136	136
U, V, W (km s^{-1})	172, −97, −35	31, −75, −102	31, −75, −102

Notes.
[a] Coordinates are given for equinox J2000.0 at the observed epoch of 2001.7.
[b] These estimates are for $M = 0.58 \, M_\odot$ (log $g = 8.0$). Ages, distances, and velocities depend strongly on the assumed mass (see Section 4.2).

(Kowalski & Saumon 2006) in the blue and through collision-induced absorption due to molecular hydrogen in the infrared (Hansen 1998; Saumon & Jacobson 1999). Cool helium atmosphere WDs do not suffer from these opacities, and they are expected to show SEDs similar to blackbodies (Kowalski et al. 2007). Therefore, ultraviolet and near-infrared data are crucial for determining the atmospheric composition of cool WDs.

We use state-of-the-art WD model atmospheres to fit the optical and near-infrared photometry of our targets. The model atmospheres include the Lyα far red wing opacity (Kowalski & Saumon 2006) as well as non-ideal physics of dense helium that includes refraction (Kowalski & Saumon 2004), ionization equilibrium (Kowalski et al. 2007), and the non-ideal dissociation equilibrium of H$_2$ (Kowalski 2006). Since parallax measurements are unavailable, we assume a surface gravity of log $g = 8$ ($M \approx 0.58 \, M_\odot$). We discuss the implications of this mass assumption in Section 4.2.

We find that the observed SEDs of our targets are best matched by pure hydrogen atmosphere models. Figure 1 presents the observed and best-fit SEDs for our targets assuming a pure hydrogen atmosphere composition. The temperatures for these models range from 3730 to 4110 K. The SEDs peak around 1 μm. Even though the optical portion of the SEDs may be explained by simple blackbodies, our *J*- and *H*-band data show that they differ from blackbodies in the infrared. The pure hydrogen atmosphere models match the ultraviolet, optical, and near-infrared SEDs of our targets fairly well.

The fits for J2137+1050 and J2145+1106N are similar to the fits obtained for the halo WD candidate SDSS J1102+4113 (Hall et al. 2008). There are slight differences between the observations and these models. The synthetic *i*-band fluxes seem lower than that observed, and there are related problems with matching the *z*- and *J*-band fluxes. Systematic problems most likely exist for models below 4000 K. The models for the two coolest stars predict absorption bumps around 1 μm. These bumps have never been observed in the spectra of real WDs, indicating that the current collision-induced opacity calculations may be problematic for high-density atmospheres of cool WDs (see, e.g., Oppenheimer et al. 2001b; Bergeron & Leggett
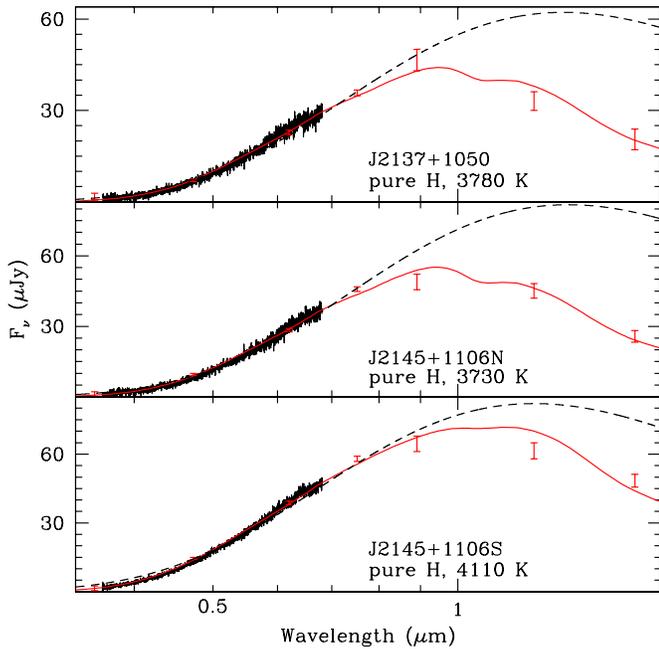
Figure 1. Observed spectra, SDSS photometry, and near-infrared photometry of our targets compared to the best-fit pure hydrogen atmosphere model spectra (solid lines, assuming $\log g = 8$) and blackbody SEDs with the same temperatures (dashed lines).

(A color version of this figure is available in the online journal.)

Figure 2. Comparison of the observed photometry (error bars) with the synthetic photometry from the best-fit pure hydrogen (solid lines), pure helium (dotted lines), and mixed H/He (dashed lines) atmosphere models. The best-fit temperatures are given in each panel.

(A color version of this figure is available in the online journal.)

2002; Kilic et al. 2009). Nevertheless, the overall SEDs of our targets agree with model predictions over the entire 0.3–1.7 μm range.

Addition of helium can improve the model fits slightly. Figure 2 shows the best-fit models assuming pure H, pure He, and mixed H/He composition. Since mixed H/He atmospheres have higher pressure than pure H atmospheres at the same temperature, the collision-induced absorption is expected to be stronger. Addition of 4%–16% helium (relative to hydrogen) into the atmosphere helps in fitting the infrared portion of the SEDs. However, these fits are marginally better than the pure hydrogen atmosphere model fits, and they are not statistically significant. The best-fit temperature values are also similar to the pure hydrogen atmosphere solutions. Hence, the choice of a pure hydrogen or mixed H/He composition with small amounts of helium does not significantly change our results. In any case, the good match between the optical spectrum and the models including Lyα absorption indicates that these WDs have hydrogen-dominated atmospheres; helium-dominated or highly helium-enriched atmospheres are ruled out (see also Hall et al. 2008).

The temperature, WD cooling age, and distance estimates for our targets based on pure hydrogen atmosphere models with $\log g = 8$ ($M = 0.58\,M_\odot$), and the cooling models by Fontaine et al. (2001) are given in Table 1. This mass assumption implies that our targets are located at 70–80 pc away from the Sun, and the WD cooling ages are 8.7 Gyr or longer. Our model fits to the individual SEDs give cooling ages of 8.7–9.7 Gyr and distances of 69 and 70 pc for the members of the J2145+1106 common proper motion system. The difference in cooling ages can be explained by a small mass difference between the two stars. These results suggest that the J2145+1106 system is a physical binary and that our model fits are reliable. Based on our proper motion measurements and assuming zero radial velocity, we also estimate the tangential velocity and Galactic
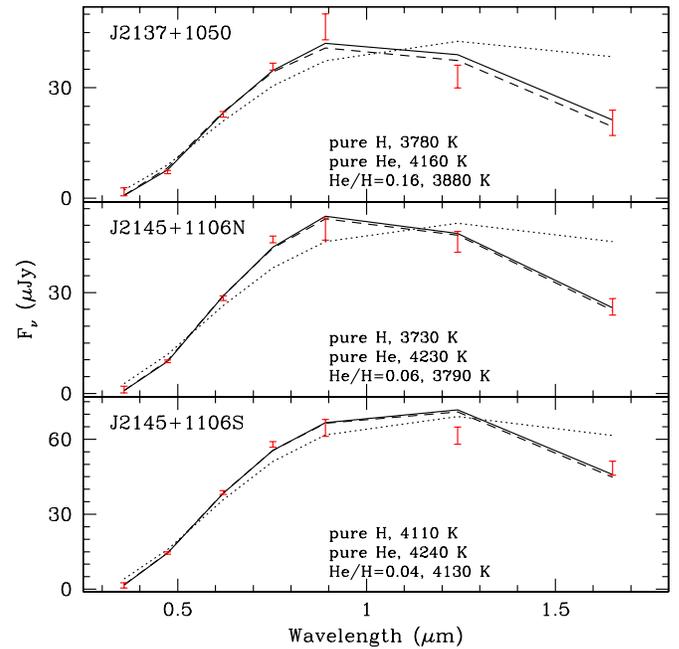
UVW velocities for our targets. These WDs display tangential velocities of 140–200 km s^{-1}.

4. THICK DISK OR HALO?

4.1. Total Ages

Bergeron et al. (2005) emphasize the importance of determining total stellar ages in order to associate any WD with the thick disk or halo. Modeling the optical and near-IR SEDs of the Oppenheimer et al. (2001a) WD sample, Bergeron et al. (2005) find that many of the WDs in that sample are fairly warm and too young to be halo WDs unless they all have masses near 0.5 $M_\odot$. They find that, with estimated temperatures of 3950–4100 K and ages of 8.8–9.1 Gyr, F351–50 and WD 0351–564 are the two most likely halo candidates in the Oppenheimer et al. (2001a) sample.

For an average mass of 0.58 $M_\odot$, our temperature estimates correspond to WD cooling ages of 9.6–9.7 Gyr for J2137+1050 and J2145+1106N. These two stars are the coolest field WDs currently known. Although the ultracool WDs discovered by Gates et al. (2004) and Harris et al. (2008) are possibly cooler than our targets, current models have problems in explaining the observed SEDs of these WDs (Bergeron & Leggett 2002). Using the initial–final mass relations of Williams et al. (2009), Kalirai et al. (2008), and Salaris et al. (2009), we estimate that a 0.58 $M_\odot$ WD would be the descendant of a 1.7–1.9 $M_\odot$ star. Such a progenitor halo star has a main-sequence lifetime of 1.0–1.3 Gyr (Marigo et al. 2008). Therefore, the total ages of our three targets range from 9.7 to 11.0 Gyr; they most likely belong to the halo or thick disk. The theoretical uncertainties due to the unknown core composition, helium layer mass, crystallization, and phase separation are on the order of 1–2 Gyr for these ages (Wood 1992; Montgomery et al. 1999; M. Montgomery 2010, private communication).
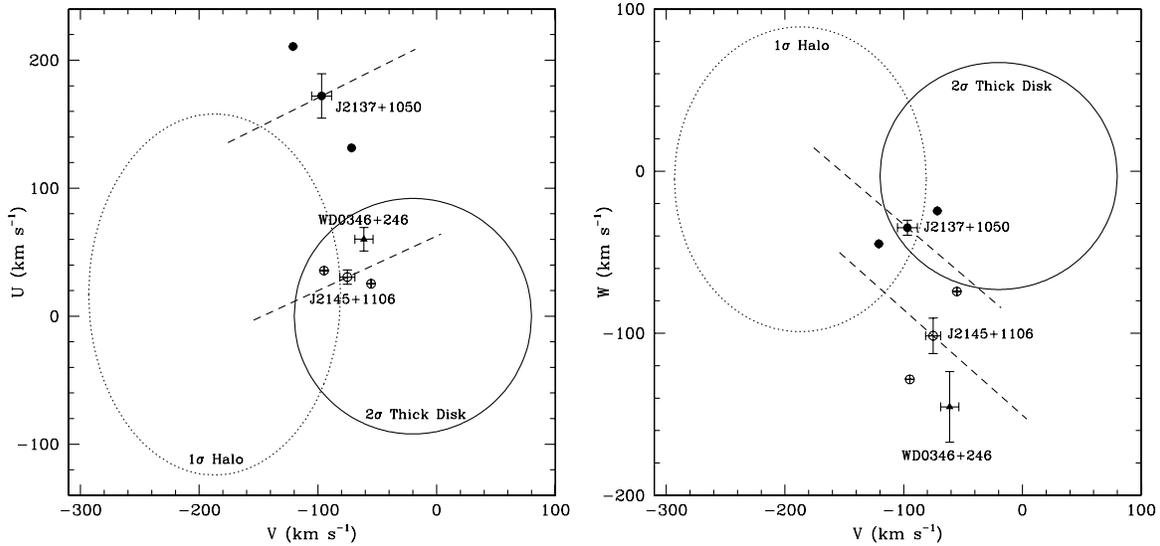
Figure 3. U, V, and W space velocities for our targets assuming 0 km s^{-1} radial velocity and log $g = 7.5$, 8.0, and 8.5 (from left to right). The points with error bars correspond to log $g = 8$. The probable halo member WD 0346+246 is shown for comparison. The 2σ velocity ellipse of the thick disk and the 1σ ellipse of the halo are also shown. The dashed lines show the effect of changing the radial velocity from -100 to $+100$ km s^{-1} (from left to right).

4.2. Kinematic Membership

Figure 3 shows the UVW velocities of our targets, assuming that they have 0 km s^{-1} radial velocities, compared to the 1σ velocity ellipse of the halo and 2σ ellipse of the thick disk (Chiba & Beers 2000). The velocities for the probable halo object WD 0346+246 are also shown for comparison. The U velocity of J2137+1050 is more than 3σ different than the thick disk objects studied by Chiba & Beers (2000). Similarly, the W velocity of J2145+1106 is inconsistent with thick disk objects. The UVW velocities of the J2145+1106 binary are similar to that of WD 0346+246. The radial velocity assumption does not change these results. Negative radial velocities bring the UVW velocities closer to the 1σ distribution for the halo, and positive radial velocities move them away from the 2σ thick disk distribution (see the dashed lines in Figure 3). Hence, both J2137+1050 and J2145+1106 systems most likely belong to the halo.

Without a parallax measurement, our age, distance, and velocity estimates are of course uncertain. A log g of 8.5 ($M = 0.9\,M_\odot$) would imply WD cooling ages of 10.1–10.6 Gyr and UVW velocities that are still inconsistent with the 2σ thick disk velocity distribution. Likewise, a log g of 7.5 ($M = 0.3\,M_\odot$) would imply WD cooling ages of 4.1–5.0 Gyr and UVW velocities that are even more inconsistent with the thick disk sample (see Figure 3). The main-sequence lifetimes would be greater than the age of the universe unless the systems are unresolved double degenerates. An additional constraint is that J2145+1106 is a binary with a separation of 10″ (700 AU, assuming log $g = 8$). This separation is too large to cause any effect on the evolution of each component, and it is small enough that the system can survive the gravitational perturbations from passing stars or Galactic tides for billions of years (Jiang & Tremaine 2010 demonstrate that more than 99.9% of the binary stars with initial separations of 0.017 pc ($\approx$3500 AU) survive for a Hubble time). A scenario involving low-mass WDs would require both components of the J2145+1106 system to be double degenerates, which seems unlikely. In addition, our pure hydrogen atmosphere models with log $g = 8$ fit the SEDs better than the models with log $g = 7.5$, indicating that our targets are not likely to be low-mass WDs.
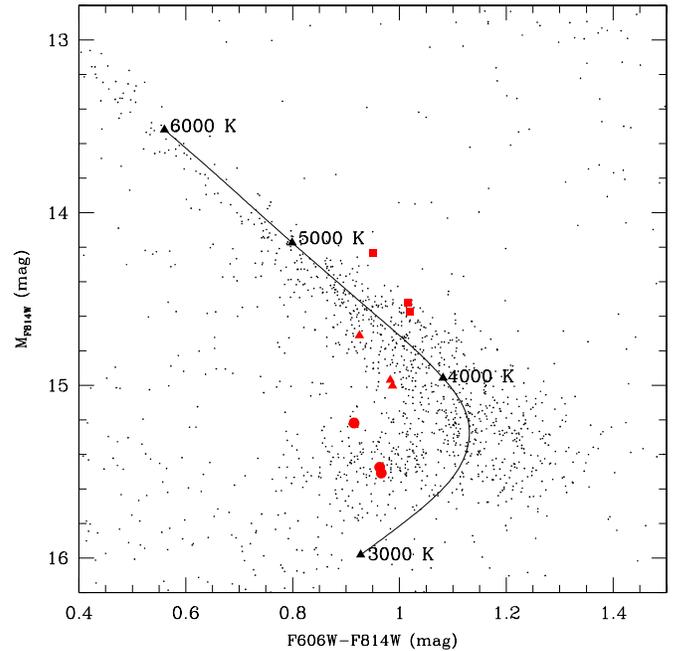

Figure 4. Color–magnitude diagram of the WDs in the globular cluster NGC 6397 (small dots; Hansen et al. 2007) and our three halo WD candidates assuming log $g = 7.5$, 8.0, and 8.5 (from top to bottom). The NGC 6397 WD sequence is de-reddened by $E(F606W - F814W) = 0.16$ and vertically shifted by $\mu = 12.0$ mag (Kowalski 2007). The errors in reddening and distance modulus are on the order of 0.03 and 0.06 mag, respectively. The solid line shows the colors for 0.53 $M_\odot$ WDs with $T_{\rm eff} = 3000$–6000 K.

(A color version of this figure is available in the online journal.)

Figure 4 displays a color–magnitude diagram of the point sources in the region that encloses the WD population of the globular cluster NGC 6397 and our three halo WD candidates assuming log $g = 7.5$, 8.0, and 8.5. We use our best-fit WD model spectra to derive synthetic photometry in the $F606W$ and $F814W$ filters. Depending on the mass, our targets can fall on multiple parts of the WD cooling sequence of NGC 6397. If they are *similar* to the WDs in NGC 6397, they should have masses ranging from 0.5 $M_\odot$ to 0.9 $M_\odot$ (log $g = 7.9$–8.5).

Kalirai et al. ([2009](#)) find the masses of the brightest WDs in the globular cluster M4 to be 0.53 $M_\odot$. This is a reasonable lower limit for our targets assuming single star evolution. At 0.53 $M_\odot$, our targets would have WD cooling ages of 8.0–9.1 Gyr, distances of 72–81 pc, and progenitor masses of 1.25–1.48 $M_\odot$ (Williams et al. [2009](#); Kalirai et al. [2008](#)). The main-sequence lifetimes would be 1.7–2.8 Gyr for the progenitor halo stars (Marigo et al. [2008](#)), and the total ages would be 9.7–11.9 Gyr. The Galactic space velocities would be inconsistent with the thick disk velocity distribution.

5. CONCLUSIONS

J2137+1050 and J2145+1106 are cool WDs with hydrogen-dominated atmospheres. Our effective temperature estimates of 3730–3780 K make J2137+1050 and J2145+1106N the coolest WDs known in the solar neighborhood. Our best-fit models imply total ages of $\approx$10–11 Gyr, distances of 70–80 pc, and Galactic space velocities that are inconsistent with thick disk population within 2σ. We conclude that these targets most likely belong to the halo. However, trigonometric parallax observations are required in order to constrain the distances, masses, and ages of our targets accurately. Such observations are currently underway at the MDM 2.4 m telescope.

Like WD 0346+246 and SDSS J1102+4113 (Bergeron [2001](#); Hall et al. [2008](#)), our three halo WD candidates have hydrogen-rich atmospheres. The oldest WDs are likely to accrete from the interstellar medium within their $\sim$10 Gyr lifetimes and end up as hydrogen-rich WDs even if they start with a pure helium atmosphere. However, the current sample of halo WD candidates is not large enough to conclude that most or all of the oldest WDs are hydrogen rich. Observations of larger samples of field WDs will be necessary to check whether all WDs turn into hydrogen-rich atmosphere WDs or not (see the discussion in Kowalski & Saumon [2006](#)).

The three targets that we present here make up only a small fraction of the halo WD candidates in our proper motion survey. Follow-up observations of these targets will be necessary to confirm many more halo WD candidates that can be used to study the age and age dispersion of the Galactic thick disk and halo. Already we can see, however, that these halo (or possibly thick disk) WDs indicate a gap of 1–2 Gyr between the star formation in the halo and the star formation in the disk at the solar annulus. Our observations further demonstrate that deep, wide-field proper motion surveys ought to find many old halo WDs. Using the Liebert et al. ([1988](#)) WD luminosity function for the Galactic thin disk and a single burst 12 Gyr old population with 10% and 0.4% local normalizations for the thick disk and halo, we estimate that there are 3200 thick disk and 140 halo WDs per 1000 $\deg^2$ (for a Galactic latitude of 45°) down to a limiting magnitude of $V = 21.5$ mag (our survey limit). Pushing the limiting magnitude down to $V = 24$ mag and assuming 50% sky coverage, we estimate that future surveys like the Pan-STARRS and Large Synoptic Survey Telescope (LSST) will image $\sim$1.3 million thick disk and $\sim$80,000 halo WDs. These surveys will be invaluable resources for halo WD studies.

Facilities: MMT (Blue Channel Spectrograph and MMIRS)

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