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Discovery of New Ultracool White Dwarfs in the Sloan Digital Sky Survey

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ABSTRACT

We report the discovery of five very cool white dwarfs in the Sloan Digital Sky Survey (SDSS). Four are ultracool, exhibiting strong collision induced absorption (CIA) from molecular hydrogen and are similar in color to the three previously known coolest white dwarfs, SDSS J1337+00, LHS 3250 and LHS 1402. The fifth, an ultracool white dwarf candidate, shows milder CIA flux suppression and has a color and spectral shape similar to WD 0346+246. All five new white dwarfs are faint ($g > 18.9$) and have significant proper motions. One of the new ultracool white dwarfs, SDSS J0947, appears to be in a binary system with a slightly warmer ($T_{eff} \sim 5000K$) white dwarf companion.

Subject headings: Stars: atmospheres— Stars: individual(SDSS J0947+44, SDSS J1220+09, SDSS J1001+39, SDSS J1403+45, SDSS J0854+35) — White Dwarfs

1. Introduction

White dwarf stars with $T_{eff} < 4000K$ are of great interest for several reasons. End-stage remnants of main sequence stars with masses less than about $8M_{\odot}$, they represent

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some of the oldest objects in the galaxy. As such they give direct information about star formation during the Galaxy's earliest epochs. Since white dwarfs continue to cool and fade with time, the very coolest can be used place lower limits on the ages of various galactic components. In addition, recent microlensing searches have suggested that there may be a significant population of white dwarfs in the galactic halo (Alcock et al. 2000). These fossil remains of an ancient stellar population could offer a window into the early stages of the galaxy and its formation.

Recent theoretical progress in understanding the evolution of white dwarfs (Hansen 1998; Saumon & Jacobson 1999) at temperatures below $6000K$ has helped to refocus the search for these objects. Ultracool white dwarfs ($T_{eff} < 4000K$) with hydrogen in the atmosphere will exhibit a unique spectral signature due to collision induced absorption (CIA) by molecular hydrogen. Such absorption results in a bluer spectrum, with a significant flux suppression red-ward of about 6000 Å, relative to a blackbody SED.

To date, only three ultracool white dwarfs with strong CIA flux suppression have been observed – LHS 3250 (Harris et al. 1999, 2001; Oppenheimer et al. 2001b), SDSS J133739.40+0001428 (hereafter referred to as SDSS J1337; Harris et al. 2001) and LHS 1402 (Oppenheimer et al. 2001a; Salim et al. 2003). These studies have dramatically confirmed the general predictions of the models. However, detailed agreement between model and observed spectra is very poor, making accurate temperature and age estimates impossible. For example, model predictions vary for different atmospheric composition and mass, but all predict a spectral feature due to H_2 at about 7500 - 8000 Å. None of the observed spectra have shown any evidence for this feature.

There is a second group of ultracool white dwarfs that exhibit milder CIA flux suppression. This group includes WD 0346+246 (Hambly, Smartt & Hodgkin 1997; Hodgkin et al. 2000; Oppenheimer et al. 2001b), LHS 1126 (Bergeron et al. 1994; Bergeron, Ruiz & Leggett 1997), and GD392B (Farihi 2004), all of which have data at wavelengths above 10,000 Å. These studies found a significant flux deficiency in the near-infrared (1-2 microns), which confirms the presence of CIA in these stars and thus their classification as ultracool white dwarfs. There are also a handful of cool white dwarfs which may belong to this second group, including a wide binary pair of white dwarfs, SSSPM J2213-7514 and SSSPM J2213-7515 (Scholz et al. 2002), F351-50 (Ibata et al. 2000) and CE 51 (Ruiz & Bergeron 2001), which is in a binary system with an M star. However, no infrared data exist for these objects as yet, and their colors and optical spectra are not conclusive evidence that they are ultracool.

The unusual colors of ultracool white dwarfs led to predictions (Harris et al. 1999; Hansen 2000) that they should be detectable in the Sloan Digital Sky Survey (SDSS; York et al. 2000, Abazajian et al. 2003, Abazajian et al. 2004, Gunn et al. 1998, Stoughton et al. 2002). The colors of these coolest white dwarfs lie in a region of color-color space that is distinct from that of most stars including higher temperature white dwarfs. This region is sparsely populated and strongly overlaps the region where high redshift ($z > 3$) QSOs are found (Richards et al. 2002). In fact, two ultracool white dwarfs were picked up in the commissioning data of the SDSS, one of which was a new discovery (SDSS J1337+00) and one which was previously known (LHS3250) (Harris et al. 2001; Luyten 1976). Both of these objects were targeted as QSOs. However, cool white dwarfs with pure helium atmospheres or those with weak CIA are less likely to be targeted for spectral observation since these will have colors which overlap the locus of ordinary stars.

In this paper we report the discovery of new ultracool white dwarfs in the SDSS. We have found four stars exhibiting strong CIA, similar to LHS 3250 and SDSS J1337+00, more than doubling the number of known ultracool white dwarfs with strong flux suppression. We also report the discovery of a fifth star, an ultracool white dwarf candidate, which shows a milder suppression and has colors closer to those of the second group exemplified by WD 0346+246.

2. Observations

Ultracool white dwarfs exhibiting strong CIA have a high probability of being selected for spectroscopic observations by SDSS as possible high redshift quasars as well as cool white dwarfs (Harris et al. 2001). We have performed a thorough search of all SDSS (Pier et al. 2003; Smith et al. 2002; Hogg et al. 2001) spectral data available as of April 2004 (approximately 50% of the total number of spectra that will ultimately be targeted by SDSS). All spectra were obtained with the SDSS 2.5 m telescope multifiber spectrographs, which cover 3800 - 9200 Å, at a spectral resolution of 1800 (York et al. 2000). Because the spectra of ultracool white dwarfs are featureless they are classified as unknown by the SDSS spectroscopic pipeline, and we visually examined all SDSS unknown spectra. The unique spectral shape of the ultracool white dwarfs stood out dramatically from the other objects in this category.

The five new ultracool white dwarfs reported here are SDSS J094722.98+445948.5, SDSS J122048.65+091412.1, SDSS J100103.42+390340.4, SDSS J140324.66+453332.6 and SDSS J085443.33+350352.7 (hereafter referred to as SDSS J0947, SDSS J1220, SDSS J1001, SDSS J1403 and SDSS J0854, respectively). Finding charts for each new star are shown in figure 1. Their positions, proper motions and colors are given in Table 1. We also recovered the ultracool white dwarfs previously found (or recovered) in SDSS, LHS 3250 and SDSS J1337.

Preliminary proper motions were calculated using the SDSS and USNO-B catalog positions, but in at least two cases these proper motions were clearly unreliable. We hence returned to the POSS I, II and SDSS images and obtained proper motion measurements by direct reduction. The five new objects all have highly significant proper motions, and SDSS J0947 has a proper motion companion at a distance of 20" to the northeast. The SDSS colors and luminosity of this object suggest that it is also a white dwarf, though of a higher temperature.

The colors of the new white dwarfs are shown in Figure 2. For comparison we have also plotted the other known ultracool white dwarfs[9] as well as the locus of points for a sample of normal white dwarfs in the SDSS (Kleinman et al. 2004). The unusual colors of the four new stars with strong CIA flux suppression - SDSS J0947, SDSS J1220, SDSS J1001 and SDSS J1403 – are evident in this plot. Based on their colors, which fall well apart from the locus of normal white dwarfs, two of these objects were targeted for spectral observation as possible QSO candidates and two were targeted by the category SERENDIPITY-DISTANT as having colors distant from the stellar locus. SDSS J0854, which exhibits milder CIA suppression, lies much closer to the locus of warmer white dwarf colors and was targeted as a carbon star. However, the spectra for all five new stars are distinctive as can be seen in Figure 3. All are featureless and show a noticeable flux suppression at wavelengths longer than about 6000 Å. This suppression is especially strong in SDSS J0947, SDSS J1001, SDSS J1220 and SDSS J1403. The spectra of SDSS J0947 and SDSS J1001 are very similar to each other and also to LHS 3250. SDSS J1403 exhibits the most severe flux suppression, while the spectrum of SDSS J1220 is somewhat more sharply peaked than the others, with a steeper slope blueward of the peak.

3. Temperature and Atmospheric Composition

Model atmosphere calculations indicate that strong CIA requires a temperature below 4000 K, and previous studies of these stars have favored atmospheres dominated by helium, although even helium-rich models fail to accurately reproduce the observed spectra in detail (Bergeron & Leggett 2002). The small number of ultracool white dwarfs that have been observed has also hampered progress toward a better understanding of their composition and properties. However, the addition of five new new stars allows us to begin a rough

[9]SDSS colors for ultracool white dwarfs without SDSS data were estimated using the photometric transformations of Fukugita et al. (1996), expected to be accurate to about 0.1 mag. The one exception to this was the $r - i$ color of LHS 1402 which we extracted from its shape-calibrated spectrum (Oppenheimer, private communication 2004). We were unable to obtain sufficient color data for F351-50 to estimate SDSS colors.

classification of these objects based on their colors and amount of CIA suppression. There are two rough groupings of ultracool white dwarfs discovered so far. (However we note that this grouping may not necessarily indicate any underlying physical distinction between the stars other than temperature.)

In the first group are SDSS J1337, LHS 3250, SDSS J0947, SDSS J1220, SDSS J1001, LHS 1402 and SDSS J1403. All seven lie in the same region of color-color space, well below the locus of normal white dwarfs, and exhibit strong CIA suppression. This indicates temperatures below about $4000K$. Previous temperature estimates for LHS 3250, SDSS J1337 and LHS 1402 have been in the broad range of $2000-4000K$, and our four new white dwarfs are also likely to have temperatures in this range. SDSS J1001 is likely to be similar in temperature to SDSS J1337, while SDSS J0947 is probably a bit warmer. If the relative position in color-color space indicates a progression downward in temperature as the cool white dwarfs fall farther from the cool end of the normal white dwarf locus, SDSS J1403 may be the coolest white dwarf yet discovered. While the spectra of SDSS J1001, SDSS J0947 and SDSS J1403 are similar to LHS 3250, trigonometric parallaxes and detailed model fitting will be necessary to determine if they are also likely to be overluminous, He-rich, low mass binaries as suggested for LHS 3250 (Harris et al. 1999; Bergeron & Leggett 2002).

The fourth new star, SDSS J1220, shows significant CIA suppression, but lies a bit further apart in color space from the others in the first grouping. Its spectral shape exhibits a relatively sharp peak, with a steep fall-off in flux both before and beyond about 6000 Å, which may indicate a different atmospheric composition from the others. However, until more detailed model comparisons can be made no strong conclusions are possible. We expect that this object also lies in the broad temperature range of $2000 - 4000K$, possibly toward the cooler end.

The second grouping of ultracool white dwarfs includes WD 0346+24, F351-50, GD392B and LHS 1126, along with the possible ultracool white dwarf candidates SSSPM J2231-7514, SSSPM J2231-7515, and the new star SDSS J0854. All of these stars lie close to the normal white dwarf locus in color space and cannot be distinguished from the locus of ordinary stars based on color alone. They exhibit milder CIA flux suppression, and may have temperatures closer to $4000K$ than those in the first grouping.

Like all three of the previously known ultracool white dwarfs, none of our new white dwarfs exhibits the H_2 feature at roughly 8000 Å(which is more pronounced in models with pure H atmospheres), as predicted by the models despite the use of the latest opacities calculated for H_2 (Borysow, Jørgensen, & Fu 2001; Jørgensen et al. 2000). Some improvement in either the opacities or the models (e.g. Kowalski & Saumon 2004, Iglesias et al. 2002) will be needed to fit these spectra and extract more accurate estimates of the temperatures and compositions of these stars.

4. Disk or Halo?

Assigning membership of these new stars to a particular component of the galaxy is problematic. Estimating distances, and thus tangential velocities, is difficult with so few known objects of this type. No color magnitude relation (CMR) yet exists and because of the dramatically different colors of these objects, the CMR for normal cool white dwarfs is inappropriate. Extracting absolute magnitude estimates from comparison to theoretical models is unreliable. For example, LHS 3250 has a parallax distance measurement which implies an absolute magnitudes much brighter than predicted by models of normal mass, hydrogen atmosphere white dwarfs that have cooled to temperatures where CIA becomes significant in the optical spectra.

The parallax distance measurement for LHS 3250 allows an accurate determination of $M_V = 15.72 \pm 0.04$ (Harris et al. 1999). If we assume a similar absolute magnitude for the new ultracool white dwarfs in the first group, we find, for SDSS J0947, a distance of $d \sim 47$ pc and a corresponding $v_{tan} \sim 20$ km s^{-1}. For SDSS J1001, we find $d \sim 64$ pc and $v_{tan} \sim 107$ km s^{-1}, while for SDSS J1403 we obtain $d \sim 44$ pc and $v_{tan} \sim 60$ km s^{-1}. Likewise, SDSS J1220, which has the highest proper motion, has $d \sim 64$ pc and $v_{tan} \sim 154$ km s^{-1}. Furthermore, SDSS J0947 has a companion with common proper motion: SDSS J094724.45 +450001.8 has colors consistent with a WD of $T_{eff} \sim 5000K$ at a distance of about 60 pc with a tangential velocity of 25 km s^{-1}. If this distance is correct, then like LHS 3250 the absolute magnitude of SDSS J0947 is brighter than that predicted by the models for a cool halo WD of normal mass, and it adds to the evidence that it is a disk star with a large radius and small mass.

We can use a similar approach for ultracool white dwarfs in the second group, assuming the absolute magnitude of SDSS J0854 is similar to that of WD 0346+246, which has $M_V = 16.8 \pm 0.3$ based on its parallax distance (Hambly et al. 1999). For SDSS J0854 we find $d \sim 41$ pc and $v_{tan} \sim 43$ km s^{-1}.

A more conservative approach for all of the new ultracool white dwarfs is to consider a value for the absolute magnitude of $M_V = 16.5 \pm 1.0$, following Salim et al. (2003). This range encompasses a wide suite of model predictions for an $m = 0.6 M_{\odot}$, pure H or mixed H/He white dwarf which exhibits CIA suppression. The results are given in Table 1. Based on these estimates of v_{tan}, it is clear that SDSS J0947 and SDSS J0854 are members of the galactic disk, and SDSS J1403 probably is as well. SDSS J1001 may be either disk or halo;

however, if it has the bright $M_V < 16$ required for the larger values of v_{tan}, it must also have a large radius and low mass similar to that implied for LHS 3250 (Harris et al. 2001). SDSS J1220 is likely to be a halo white dwarf, which makes its unusual colors and steep flux suppression even more interesting. It is the only ultracool white dwarf known that can be a halo star with normal mass that has cooled to a temperature substantially lower than WD 0346+246. Ultimately, of course, trigonometric parallax measurements will be necessary to fully understand these stars.

Based on the six stars with strong CIA detected in ~ 4330 deg^2 of sky observed for SDSS spectra through April 2004, we find 0.0014 deg^{-2} ultracool WDs with $i < 20.2$ (the magnitude limit for selection of QSO candidates), or approximately $R < 19.8$. This density is somewhat higher than found by Oppenheimer et al. (2001a) who found one star (LHS 1402) in 4200 deg^2 with $R < 19.8$ and $\mu > 330$ mas yr^{-1} (three of our six stars are within these limits), and it is consistent with the LHS Catalog that has two stars with $R < 18$ and $\mu > 500$ mas yr^{-1} (although the LHS limiting magnitude varies over the sky). To estimate their space density, we note that nearly all ultracool WDs will be selected for spectra by one or both of the QSO selection algorithms. The magnitude limits are $i < 19.1$ for low-z QSO candidates and $i < 20.2$ for redder high-z candidates. In fact, all six strong-CIA stars were flagged by the QSO selection procedure, and four were assigned fibers as QSO candidates[10]. Assuming that these four stars are all like LHS 3250 with $M_r = 15.47$, and summing the inverse of their potential discovery volumes gives a space density of 3.0×10^{-5} pc^{-3}. This value is very uncertain because of the uncertain distance and luminosity of most of the stars, but is similar to the density of the disk white dwarf luminosity function at the faintest measured luminosity bin (Leggett, Ruiz, & Bergeron 1998). We note that our estimate reflects a mix of various galactic components.

Finally, we note that the status of SDSS J0947 as a member of a binary system is far from unique. CE 51 has a main sequence companion, GD392B has a probable white dwarf companion and SSSPM J2231-7514 and SSSPM J2213-7515 are a wide binary pair. Thus, if these latter three stars are confirmed as ultracool, $\sim 30\%$ of the known ultracool white dwarfs would be in binary systems.

In summary, we have discovered five new ultracool white dwarfs in the SDSS. Four have

[10]Of the other two, SDSS J1001 was too faint for low-z selection so was flagged as QSO_MAG_OUTLIER, and SDSS J1403 had colors in the A-star reject box so was flagged as QSO_REJECT. Both were observed anyway by the backup SERENDIPITY_DISTANT. Because SERENDIPITY and other non-QSO selection categories are not complete, we omit these two stars from the calculation of space density. The faint magnitude limits for these categories imply large discovery volumes and thus we expect the density contributions will be small in any case.

colors and spectra indicating strong CIA, and one appears to have the strongest CIA of any star discovered to date. Only one star has a proper motion sufficiently large that it is likely to be a halo star with low luminosity and normal mass. Three of the others have smaller proper motions indicating that they are probably disk stars with younger ages, higher luminosities and smaller masses, and one of these three has a warmer white dwarf companion with a photometric distance supporting the small-mass interpretation. The fifth star has a proper motion that could be either disk or halo, but for higher tangential velocities it must also have a high luminosity and low mass. None of the spectra show bands of H_2 predicted by current white dwarf atmosphere models, and we find a rough estimate of the density of ultracool white dwarfs of about 3.0×10^{-5} pc^{-3}.

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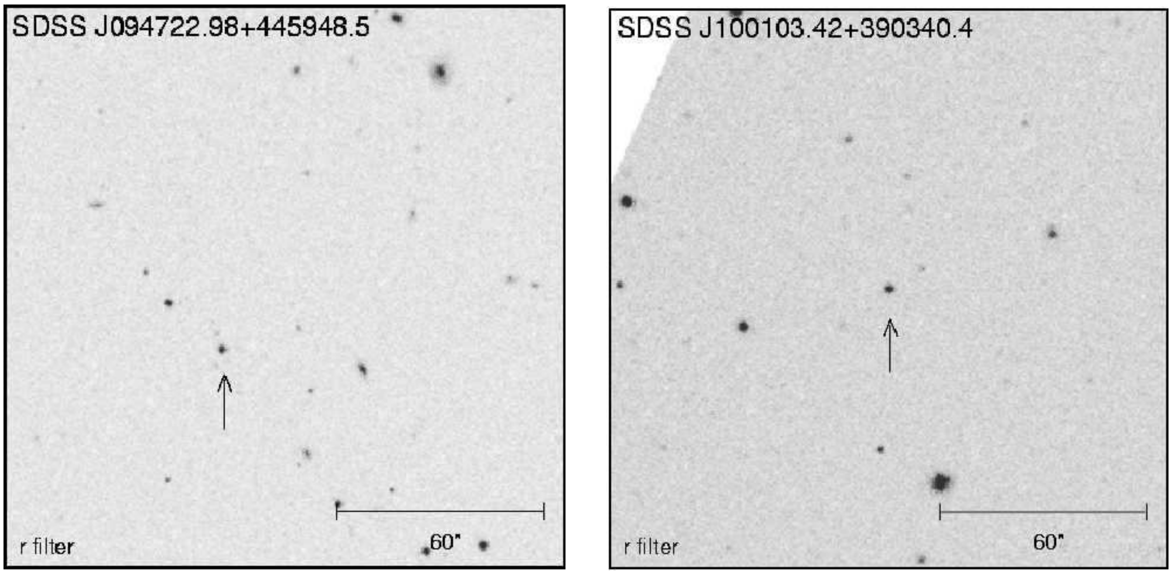

Fig. 1.— (a) Finding charts for new ultracool white dwarfs from r band SDSS images. North is up, east is to the left. Epochs are given in Table 1.

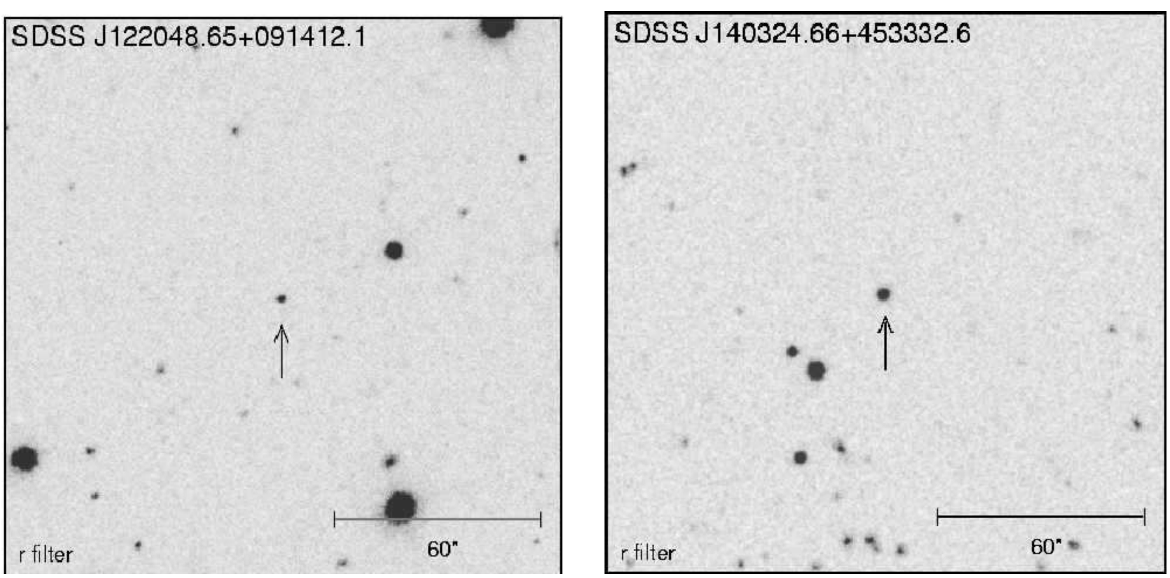

Fig. 1.— (b)

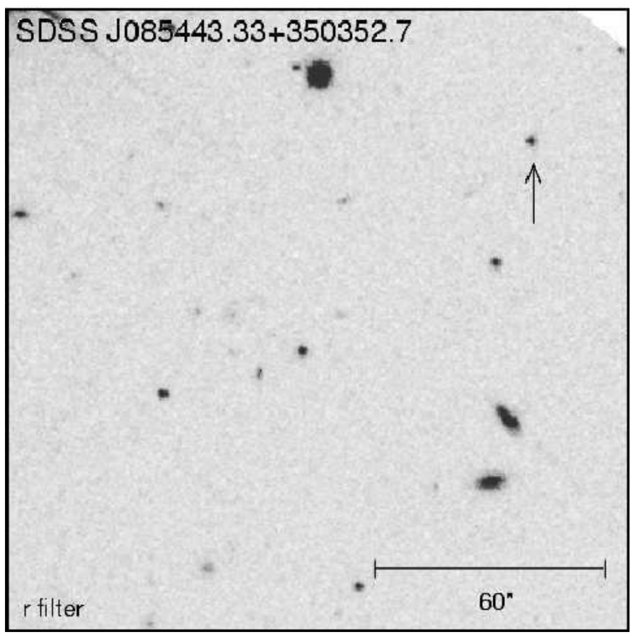

Fig. 1.— (c)

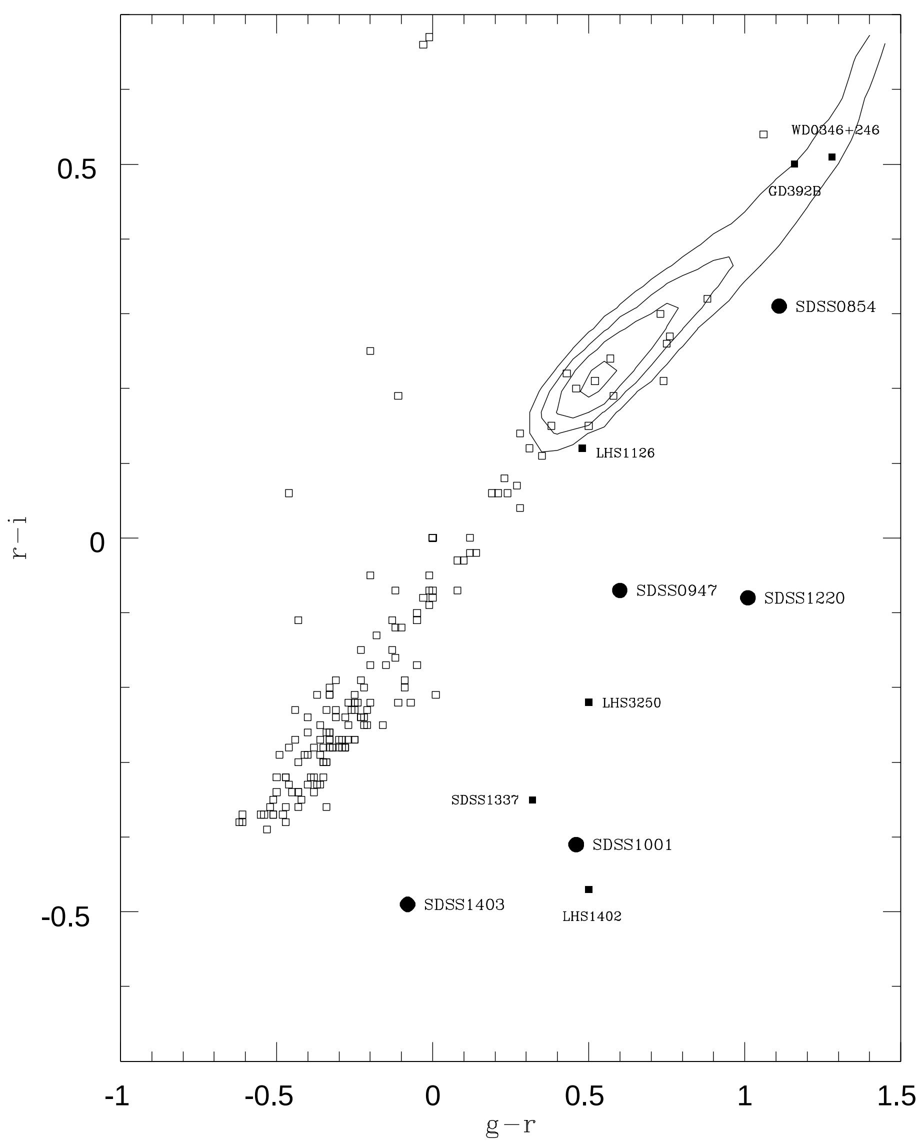

Fig. 2.— Color-color diagram showing five new white dwarfs (solid circles) and previously known ultracool white dwarfs (solid squares) for which we were able to estimate SDSS colors (see text for more details). A sample of normal white dwarfs (open squares) and contours which show the colors of nondegenerate stars in SDSS are included for comparison.

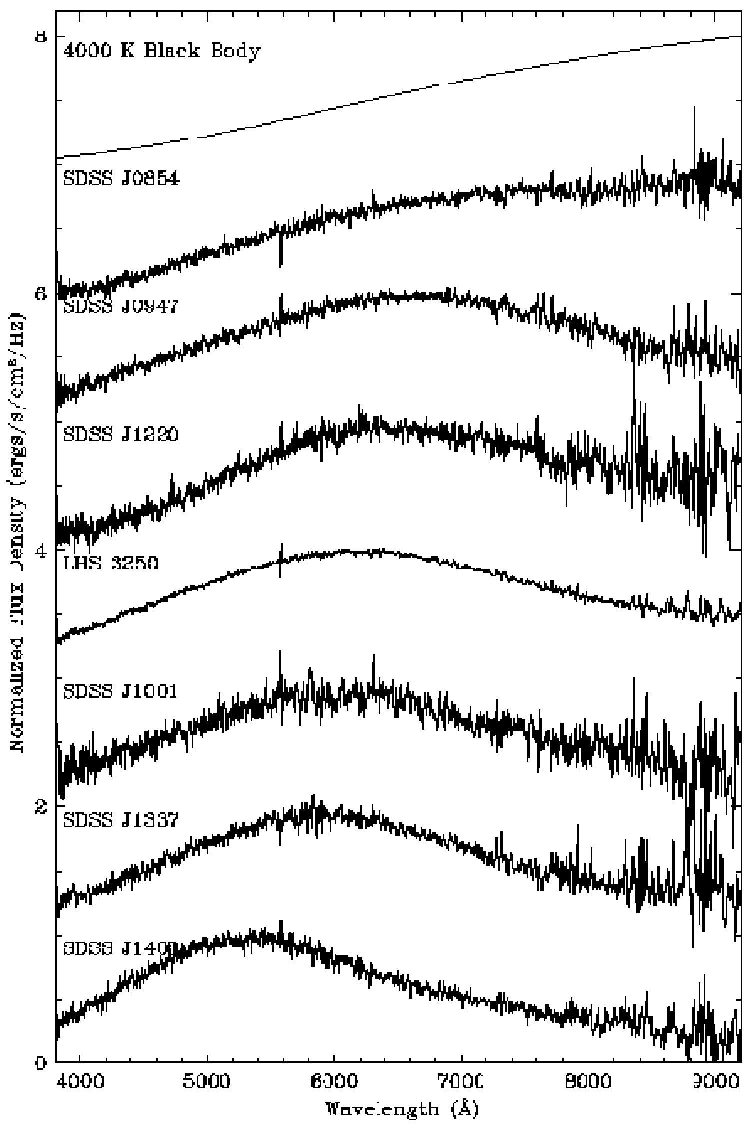

Fig. 3.— Spectra for seven ultracool white dwarf stars observed in the the SDSS data, including five new stars. Spectra are offset vertically from each other and a 4000 K blackbody SED is also shown for comparison. (Spectra have been smoothed by 5 pixels.)

Table 1. Observational Data

Parameter	SDSS J0947	SDSS J1220	SDSS J1001	SDSS J0854	SDSS J1403
RA	09 47 23.0	12 20 48.7	10 01 03.4	08 54 43.3	14 03 24.7
dec	44 59 49	09 14 12	39 03 40	35 03 53	45 33 33
μ (mas yr^{-1})	86	504	353	223	284
μ_α (mas yr^{-1})	74 ± 4	-341 ± 15	-301 ± 3	-133 ± 5	-271 ± 3
μ_δ (mas yr^{-1})	45 ± 3	-372 ± 15	-185 ± 3	-179 ± 5	-84 ± 3
u	20.71	22.40	21.39	23.63	20.14
g	19.45	20.35	20.04	20.49	18.93
r	18.85	19.34	19.58	19.38	19.02
i	18.92	19.42	19.99	19.07	19.51
z	19.40	19.89	20.51	18.92	19.82
d (pc)	21-52	28-71	28-71	30-74	19-49
v_{tan} (km s^{-1})	8-21	68-170	47-119	31-78	26-66
Julian Epoch	2002.023	2002.192	2002.998	2002.850	2003.176
SDSS spectra information:					
MJD-plate-fiber	52672-1202-33	52672-1230-58	53033-1356-280	52964-1211-395	53115-1467-401

[a]Coordinates are given for equinox J2000.0