COOL VERSUS ULTRACOOL WHITE DWARFS

J. Farihi¹,²

ABSTRACT

A preliminary $BVRIJK$ analysis of the white dwarfs SSSPM J2231$-$7514 and SSSPM J2231$-$7515 is presented. Although both stars were reported to have $T_{\text{eff}} < 4000$ K, the analysis here indicates $T_{\text{eff}} \approx 4250$ K for both SSSPM J2231$-$7514 and SSSPM J2231$-$7515. Given substantial scientific interest in the coolest extant degenerate stars, it is necessary to distinguish sub 4000 K objects from the bulk of cool white dwarfs. This analysis reiterates the importance of near infrared observations in constraining the spectral energy distributions and effective temperatures of the coolest white dwarfs and briefly discusses their possible origins.

Subject headings: binaries: visual — stars: fundamental parameters — stars: individual (SSSPM J2231$-$7514, SSSPM J2231$-$7515) — white dwarfs

1. INTRODUCTION

The study of cool white dwarfs with $T_{\text{eff}} > 4000$ K has been artfully mastered by P. Bergeron and collaborators. They have shown that with $BVRIJK$ photometry alone, the effective temperature and atmospheric composition of cool degenerates can be determined with a high degree of accuracy. In addition, if the white dwarf has a known distance or Balmer lines, then the surface gravity (hence mass and radius) can be determined quite well. Comparisons of predicted versus measured absolute magnitudes and radii for white dwarfs with trigonometric parallaxes have confirmed their findings (Bergeron, Ruiz & Leggett 1997; Leggett, Ruiz, & Bergeron 1998; Bergeron, Leggett, & Ruiz 2001).

Known ultracool white dwarfs ($T_{\text{eff}} < 4000$ K) are spectrally distinct objects and should be considered a separate class of degenerate star. The overall shape of their emergent flux is strongly influenced by opacity due to collisions between H$_2$ molecules in pure hydrogen atmospheres or between He and H$_2$ in mixed atmospheres (for a great review, see §2 of

¹Gemini Observatory, Northern Operations, 670 North A’ohoku Place, Hilo, HI 96720; jfarihi@gemini.edu
²Department of Physics & Astronomy, University of California, Los Angeles, CA 90095
Bergeron 2001). This collision induced absorption (CIA) has been observed to suppress
flux at near infrared and red optical wavelengths. At present there exist only 4 known
ultracool white dwarfs with effective temperature estimates based on published optical and
near infrared data (Harris et al. 1999, 2001; Hodgkin et al. 2000; Bergeron 2001; Bergeron
& Leggett 2002; Oppenheimer et al. 2001a; Farihi 2004).

This paper presents an examination of a few ultracool white dwarf candidates based on
existing data. A preliminary optical plus near infrared spectral energy distribution analysis
of the cool white dwarfs SSSPM J2231−7514 and SSSPM J2231−7515 supports effective
temperatures near or above 4250 K and little, if any, flux suppression due to CIA. A brief
examination of the data available on F351-50 indicates a possible effective temperature above
4000 K as well.

2. DATA & ANALYSIS

Scholz et al. (2002) reported the discovery of a comoving pair of faint high proper motion
stars which were spectroscopically determined to be cool DC white dwarfs. These white
dwarfs are of interest because they are likely to be within 20 pc of the sun and potentially
cooler than previously known degenerates at this distance.

2.1. Photometry

Optical \textit{BVRI} photometric data were taken from Scholz et al. (2002). The \textit{BRI}
magnitudes for the white dwarfs are from the SuperCOSMOS Sky Survey (SSS) and photographic
in nature, hence the uncertainties are relatively large (Hambly et al. 2001a). These were
converted to the Johnson-Cousins system using the appropriate transformations (Blair &
Gilmore 1982; Bessell 1986; Salim et al. 2004).

The 2MASS All Sky image database (Cutri et al. 2003) shows both SSSPM J2231−7514
and SSSPM J2231−7515 at positions 22\textsuperscript{h}30\textsuperscript{m}40.08\textsuperscript{s}, 75\textdegree13'56.7" & 22\textsuperscript{h}30\textsuperscript{m}33.63\textsuperscript{s}, 75\textdegree15'25.6"
(J2000, epoch 2000 Oct 08) respectively at all three wavelengths. A comparison of the
2MASS \textit{J} band image with the digitized UKST \textit{I} band image (epoch 1993) confirms the
identity of the stars with the correct published proper motion of $\mu = 1.87'' \text{yr}^{-1}$ at $\theta = 167.5^\circ$
(Scholz et al. 2002). \textit{JHK}_s magnitudes were extracted from the 2MASS database at the
above positions. All data are listed in Table 1.
2.2. Colors & Atmosphere

The brighter and fainter binary components have $V - J$ colors of 1.94 and 2.01 respectively. This color index involves the two filters with the smallest measurement errors and are therefore the most reliable (especially compared to color indices involving $BRI$). In addition, their $V - K_s$ colors are 2.16 and 2.15 respectively, with slightly larger uncertainty in the $K_s$ magnitudes. If accurate, these colors indicate that both stars are very likely to have effective temperatures above 4000 K, regardless of atmospheric composition. In the following, log $g = 8.0$ is assumed.

White dwarfs with hydrogen atmospheres can possess near infrared colors that are bluer than those stated above (due to CIA), beginning at $T_{\text{eff}} < 5000$ K. By 4000 K, their colors will certainly be much bluer than those implied by Table 1 (Bergeron, Saumon, & Wesemael 1995; Bergeron, Ruiz & Leggett 1997; Bergeron 2001; Bergeron, Leggett, & Ruiz 2001). For cool white dwarfs with normal mass (log $g \sim 8.0$) in general, the predicted and measured $V - J$ colors for hydrogen atmospheres do not become as red as those associated with helium atmospheres. For example, $V - J$ reaches a maximum around 1.9 for log $g = 8.0$ and around 1.8 for log $g = 8.5$ in cool hydrogen atmosphere models for $T_{\text{eff}} = 4250$ K. However, colors as red as $V - J \approx 2.0$ have been observed and associated with hydrogen rich atmospheres (Bergeron, Saumon, & Wesemael 1995; Bergeron, Ruiz & Leggett 1997; Bergeron, Leggett, & Ruiz 2001).

Cool helium atmosphere white dwarfs are predicted and measured to attain colors this red in $V - J$ around $T_{\text{eff}} = 4500$ K. However, the corresponding near infrared colors for helium atmospheres are also red, with $J - K_s \gtrsim 0.3$ corresponding to a $V - J \sim 2.0$. Thus, if the 2MASS photometry is accurate, SSSPM J2231−7514 and SSSPM J2231−7515 are likely to have hydrogen rich atmospheres, but a helium rich composition cannot be ruled out. In §2.3, model fits using both hydrogen and helium atmospheres are considered.

2.3. Spectral Energy Distributions & Temperatures

$BVRIJHK$ magnitudes were converted to average fluxes following the method of Bergeron, Ruiz & Leggett (1997) and fitted with the pure hydrogen and helium model grids of P. Bergeron (Bergeron, Saumon, & Wesemael 1995; Bergeron, Wesemael, & Beauchamp 1995; 2002, private communication). A surface gravity of log $g = 8.0$ was assumed since the distance to the stars is not known. The fits are shown in Figures 1–4.

The large error bars at $BRI$ are associated with the external calibration of SSS photographic magnitudes. These errors might actually be underestimated here due to both error
propagation during the transformation to Johnson-Cousins BRI and because the external errors reported in Hambly, Irwin, & MacGillivray (2001b) were determined only for a small number of stars on plates in the equatorial zone. An illustration of the potential problem is the fact that both SSSPM J2231−7514 and SSSPM J2231−7515 have similar colors in all indices with the exception of $B−V$ where they are different by 0.4 mag (a remnant from the original photographic $B_J$). This discrepancy is almost certainly due to inaccuracies and a more conservative estimate of the errors is 0.3 mag (Hambly, Irwin, & MacGillivray 2001b). This is an important consideration when comparing the model predicted and measured fluxes at these wavelengths. One way to deal with these large uncertainties at BRI is to essentially ignore those data. Another would be to treat all data points equally, regardless of error. A decent compromise seems to be to give more weight to the VJHK data, while still using all the available data in the fit.

The resulting preliminary spectral energy distributions of both white dwarfs are matched quite well by $T_{\text{eff}} = 4250$ K pure hydrogen models. Whereas the flux of the brighter component in Figure 1 is not inconsistent with the $T_{\text{eff}} = 4500$ K model, the flux of the the fainter component in Figure 2 appears less agreeable with the higher temperature hydrogen model. The flux estimates for both stars do not show good agreement with $T_{\text{eff}} < 4250$ K hydrogen models, where significant CIA begins to suppress near infrared flux and all infrared colors become negative. Mixed H/He atmosphere models predict even more CIA for a given temperature and hence are also inappropriate (Bergeron 2001; Oppenheimer et al. 2001a). If all the data points are weighted equally, then a pure helium model is applicable, yielding $T_{\text{eff}} \approx 4500$ K for both stars (Figures 3 & 4).

The fact that the data on both stars agree quite well with models of the same $T_{\text{eff}}$ does not contradict their measured magnitude difference at $V$. This difference could be due to their relative sizes (hence their mass ratio, which is assumed to be unity here). A $0.1 − 0.2$ difference in log $g$ could explain their $\Delta V$ as could a $\sim 200$ K difference in $T_{\text{eff}}$ (Bergeron, Wesemael, & Beauchamp 1995).

3. DISCUSSION

3.1. Ultracool White Dwarf Candidates

There are only 4 white dwarfs with published optical and near infrared data supporting their status as $T_{\text{eff}} < 4000$ K degenerates. These ultracool white dwarfs are, in order of their discovery: LHS 3250, WD 0346+246, SDSS 1337+00, GD392B (Harris et al. 1999; Hodgkin et al. 2000; Harris et al. 2001; Farihi 2004). In addition, there are several white
dwarfs with published optical data that span the range from candidate to all but certain ultracool white dwarfs. These are CE 51, F351-50, LHS 1402, WD 2356-209 (Ibata et al. 2000; Oppenheimer et al. 2001a,b; Ruiz & Bergeron 2001; Salim et al. 2004), and the five new Sloan stars recently reported by Gates et al. (2004).

Near infrared photometry indicates the proper motion selected white dwarfs SSSPM J2231-7514 and SSSPM J2231-7515 both have $T_{\text{eff}} \gtrsim 4250$ K. For log $g \sim 8.0$, this would put the wide binary at a distance of around 15 pc, assuming 4500 K for the brighter and 4250 K for the fainter component. They may be the coolest white dwarfs known within 20 pc. There are only two white dwarfs with measured $\pi > 50$ mas and $T_{\text{eff}} < 4500$ K as determined by full spectroscopic and photometric analyses including near infrared data; LHS 239 & ER 8 (Bergeron, Ruiz & Leggett 1997; Bergeron, Leggett, & Ruiz 2001; Holberg, Oswalt, & Sion 2002).

As Bergeron (2003) points out, the spectral energy distributions of cool white dwarfs are not well constrained by optical data alone. Colors such as $V - I$ reach a maximum redness and then become bluer again due to CIA – yielding two possible temperatures for a given value of $V - I$ (Bergeron 2003). Hence any white dwarf study claiming sub 4000 K temperatures should present the requisite near infrared data.

Optical spectroscopy also has pitfalls. Blackbody fits to the 4300–6800 Å flux calibrated spectra of SSSPM J2231–7514 and SSSPM J2231–7515 yielded temperatures of 3810 K and 3600 K, respectively (Scholz et al. 2002). The analysis here shows these temperatures are likely to be underestimated by at least 650 K. In contrast, the blackbody fits to the 4000 – 8500 Å flux calibrated spectrum of WD 0346+246 yielded temperatures 100 – 150 K higher than $T_{\text{eff}} = 3750$ K as determined by parallax and total integrated flux (Hambly, Smart, & Hodgkin 1997; Hodgkin et al. 2000; Oppenheimer et al. 2001a). This could be because white dwarfs with significant CIA in the near infrared will have some of their flux redistributed toward higher energies. Assuming the flux calibration of Scholz et al. (2002) is correct, blackbodies simply do not provide a good estimate of $T_{\text{eff}}$ for cool white dwarfs.

The flux calibrated optical spectra of F351-50 and F821-07 (LHS 542) were fitted with 3500 K and 4100 K blackbodies respectively (Ibata et al. 2000). F351-50 was noted to have “a substantial depression of the flux redward of 6500 Å... precisely as was originally seen in WD 0346+246”, while LHS 542 is noted as having “a similar spectral shape to WD 0346+246” (Ibata et al. 2000). First, WD 0346+246 does not show flux suppression in the optical but approximates a $T \approx 3900$ K blackbody fairly well out to $\sim 9000$ Å (Hambly, Smart, & Hodgkin 1997; Hodgkin et al. 2000; Oppenheimer et al. 2001a). Second, the most reliable effective temperature determination of LHS 542 is 4720 K, based on its trigonometric parallax plus optical and near infrared photometry (Legget, Ruiz, & Bergeron 1998; Bergeron 2003).
There is certainly no flux deficit out to 2.2 µm as seen in the measured data and model fit shown in Figure 2 of Bergeron (2003) for LHS 542. Third, there is no corroborating evidence of a flux deficit in F351-50. Its optical spectrum as shown in Figure 3 of Oppenheimer et al. (2001a) appears to have a flatter slope than WD 0346+246 out to 10,000 Å and looks fairly consistent with the 4000 K blackbody plotted in the same Figure. Hence there appears to be a problem in either the flux calibration or the blackbody in Figure 1 of Ibata et al. (2000) that causes both white dwarfs to appear cooler. The 620 K difference in the effective temperatures reported for LHS 542 by Ibata et al. (2000) and Bergeron (2003), if added to the 3500 K temperature estimate for F351-50, yields 4120 K – exactly the value obtained by Bergeron (2003) as one of two possibilities for F351-50 based on optical data alone. Additional data has confirmed this higher temperature as likely (P. Bergeron 2004, private communication).

3.2. The Origin of Ultracool Degenerates

An important goal is to understand the origin of ultracool white dwarfs, both in the disk and the halo. Halo white dwarfs can be older than 10 Gyr and have therefore, according to models, had enough time to cool to sub 4000 K temperatures, regardless of atmospheric composition and mass (Bergeron, Saumon, & Wesemael 1995; Hansen 1999). Normal mass ($M \approx 0.6 M_\odot$) disk white dwarfs on the other hand, generally have not had enough time to attain ultracool temperatures with the exception of very low mass ($M \leq 0.4 M_\odot$) or very high mass ($M \geq 1.0 M_\odot$) cases (Bergeron, Saumon, & Wesemael 1995; Hansen 1999; Serenalli et al. 2001).

So far, there is both solid and tentative evidence for ultracool disk white dwarfs of low mass (Harris et al. 2001; Farihi 2004). These remnants are likely to be the products of close binary evolution rather than single stars evolved from the main sequence (Marsh, Dhillon, & Duck 1995). Possibly awaiting detection are the much fainter high mass ultracool white dwarf counterparts (Ruiz et al. 1995; Farihi 2004). Trigonometric parallax measurements will tell if any of the new Sloan ultracool white dwarfs are massive (Gates et al. 2004). The differential cooling between low, normal and high mass degenerates may be the most important reason to distinguish between white dwarfs warmer or cooler than $\sim 4000$ K. Specifically, cool and ultracool disk white dwarfs may have separate formation channels.

Given the fact that the peak flux for ultracool white dwarfs is in the optical region of the spectrum, the dearth of detections may be telling. However, the available data on the coolest degenerates is a product of the finite age of the local disk convolved with its star formation history plus the ability of various searches to identify them. Astronomers must first be confident of their ability to detect them before understanding their relative numbers,
origins, and overall astrophysical implications.

3.3. Classification of CIA White Dwarfs

Spectrally distinct stars should be classified distinctly. However, spectral assignment must depend on observed features only and be model independent. In the accepted scheme of McCook & Sion (1999) for white dwarfs, the effective temperature index is completely independent of spectral type. Therefore, any designation for white dwarfs displaying CIA would be independent from effective temperature.

Technically speaking, are white dwarfs with CIA featureless? Although potentially an extremely broad feature in pure hydrogen atmospheres, CIA is essentially a continuum opacity in all white dwarfs for which it has been observed. This opacity is virtually undetectable until very strong, where it is evident in flux calibrated optical or near infrared spectra (Harris et al. 1999; Hodgkin et al. 2000; Harris et al. 2001; Gates et al. 2004). Therefore “DC” alone may not be the most appropriate designation for these degenerates (this is especially true in light of the possibility that pure helium atmosphere stars cooler than 4000 K may exist and await discovery).

Interestingly, with the exception of the DQ9.5 star LHS 1126 (\(T_{\text{eff}} = 5400\) K, Bergeron et al. 1994), there are currently no other cool white dwarfs at temperatures significantly above 4000 K with significant CIA as evidenced by blue near infrared colors. All other white dwarfs with CIA are currently suspected to be DC13+ stars.

4. CONCLUSION

An analysis of existing data on SSSPM J2231−7514 and SSSPM J2231−7515 indicates \(T_{\text{eff}} \approx 4250\) K for both white dwarfs. This value should be considered preliminary as higher signal to noise optical and near infrared photometry is needed. If the 2MASS data are accurate, the near infrared colors of these white dwarfs are red and not consistent with significant flux suppression due to CIA. These two stars, among others, may represent the coolest effective temperatures attainable by normal mass, single white dwarf evolution in the disk of the Galaxy. Degenerates with temperatures below 4000 K, the ultracool degenerates, may be the unique signature of halo white dwarfs and disk white dwarfs of atypical mass.

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Fig. 1.— Cool hydrogen atmosphere model fits to the spectral energy distribution of SSSPM J2231–7514, assuming log $g = 8.0$ (§2.3).
Fig. 2.— Cool hydrogen atmosphere model fits to the spectral energy distribution of SSSPM J2231−7515, assuming log $g = 8.0$ (§2.3).
Fig. 3.— Cool helium atmosphere model fits to the spectral energy distribution of SSSPM J2231−7514, assuming log $g = 8.0$ (§2.3).
Fig. 4.— Cool helium atmosphere model fits to the spectral energy distribution of SSSPM J2231−7515, assuming log $g = 8.0$ (§2.3).
Table 1. Optical & Near Infrared Photometric Data

| Band | $\lambda_0(\mu m)$ | SSSPM J2231$-$7514 | SSSPM J2231$-$7515 |
|------|---------------------|---------------------|---------------------|
| $B$  | 0.44                | 17.56 ± 0.14        | 18.24 ± 0.14        |
| $V$  | 0.55                | 16.60 ± 0.05        | 16.87 ± 0.05        |
| $R$  | 0.64                | 15.89 ± 0.15        | 16.18 ± 0.15        |
| $I$  | 0.80                | 15.25 ± 0.21        | 15.45 ± 0.21        |
| $J$  | 1.25                | 14.66 ± 0.04        | 14.86 ± 0.04        |
| $H$  | 1.63                | 14.66 ± 0.06        | 14.82 ± 0.06        |
| $K_s$| 2.16                | 14.44 ± 0.08        | 14.72 ± 0.12        |

Note. — Near infrared data all have SNR > 10 and are taken from 2MASS (Cutri et al. 2003). Optical data are taken from Scholz et al. (2002) with $BRI$ converted from photographic magnitudes to the Johnson-Cousins system. The errors in $BRI$ are from Hambly, Irwin, & MacGillivray (2001b) and do not include any conversion errors.