COOL VERSUS ULTRACOOL WHITE DWARFS

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ABSTRACT

A preliminary *BVRIJHK* analysis of the white dwarfs SSSPM J2231−7514 and SSSPM J2231−7515 is presented. Although both stars were reported to have $T_{\rm eff} < 4000$ K, the analysis here indicates $T_{\rm eff} \approx 4250$ 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.

Key words: binaries: visual — stars: fundamental parameters —
stars: individual (SSSPM J2231−7514, SSSPM J2231−7515) — white dwarfs

1. INTRODUCTION

The study of cool white dwarfs with $T_{\rm eff} > 4000$ K has been artfully mastered by P. Bergeron and collaborators. They have shown that with *BVRIJHK* 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 et al. 1997, 2001; Leggett et al. 1998).

Known ultracool white dwarfs ($T_{\rm eff} < 4000$ 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 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 four 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. 2001b; 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 AND ANALYSIS

Scholz et al. (2002) reported the discovery of a comoving pair of faint high proper motion stars that 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 *BVRI* photometric data were taken from Scholz et al. (2002). The *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. 2001b). These were converted to the Johnson-Cousins system using the appropriate transformations (Blair & Gilmore 1982; Bessell 1986; Salim et al. 2004).

The Two Micron All Sky Survey (2MASS) All Sky image database (Cutri et al. 2003) shows both SSSPM J2231−7514 and SSSPM J2231−7515 at positions $22^{\rm h}30^{\rm m}40\overset{s}{.}08$, $-75°13'56\overset{''}{.}7$ and $22^{\rm h}30^{\rm m}33\overset{s}{.}63$, $-75°15'25\overset{''}{.}6$ (J2000.0, epoch 2000 October 8), respectively, at all three wavelengths. A comparison of the 2MASS *J*-band image with the digitized United Kingdom Schmidt Telescope *I*-band image (epoch 1993) confirms the identity of the stars with the correct published proper motion of $\mu = 1\overset{''}{.}87$ yr^{-1} at $\theta = 167°\!\!.5$ (Scholz et al. 2002). The JHK_s magnitudes were extracted from the 2MASS database at the above positions. All data are listed in Table 1.

2.2. *Colors and 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 that have 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 $T_{\rm eff} < 5000$ K. By 4000 K, their colors will certainly be much bluer than those implied by Table 1 (Bergeron et al. 1995a, 1997, 2001; Bergeron 2001). In general, for cool white dwarfs with normal mass ($\log g \sim 8.0$), 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

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TABLE 1
Optical and Near-Infrared Photometric Data

Band	λ_0 (μm)	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

Notes.—Near-infrared data all have S/N > 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 et al. (2001a) and do not include any conversion errors.

models for $T_{\rm eff} = 4250$ K. However, colors as red as $V - J \approx 2.0$ have been observed and associated with hydrogen-rich atmospheres (Bergeron et al. 1995a, 1997, 2001).

Cool helium atmosphere white dwarfs are predicted and measured to attain colors this red in $V - J$ around $T_{\rm eff} = 4500$ K. However, the corresponding near-infrared colors for helium atmospheres are also red, with $J - K \gtrsim 0.3$ 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 and Temperatures

The BVRIJHK magnitudes were converted to average fluxes following the method of Bergeron et al. (1997) and fitted with pure hydrogen and helium model grids (Bergeron et al. 1995a, 1995b; P. Bergeron 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 because of both error propagation during the transformation to Johnson-Cousins BRI and the fact that the external errors reported in Hambly et al. (2001a) were determined only for a small number of stars on plates in
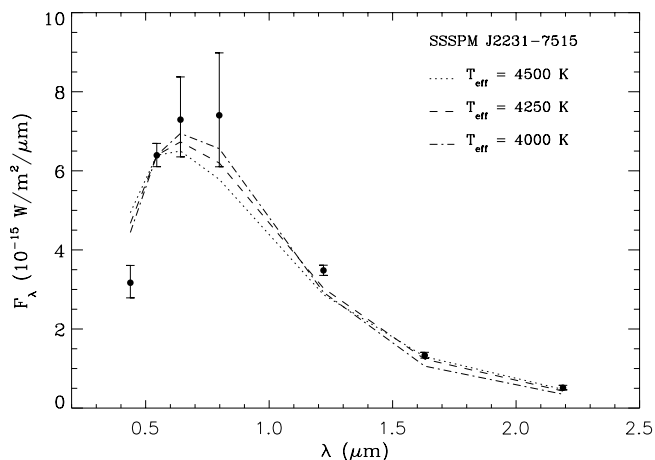

Fig. 2.—Cool hydrogen atmosphere model fits to the spectral energy distribution of SSSPM J2231−7515, assuming $\log g = 8.0$ (§ 2.3).

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 $B - V$, in which 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 et al. 2001a). 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 $T_{\rm eff} = 4250$ K pure hydrogen models. Whereas the flux of the brighter component in Figure 1 is not inconsistent with the $T_{\rm eff} = 4500$ K model, the flux of 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 $T_{\rm eff} < 4250$ K hydrogen models, in which 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;
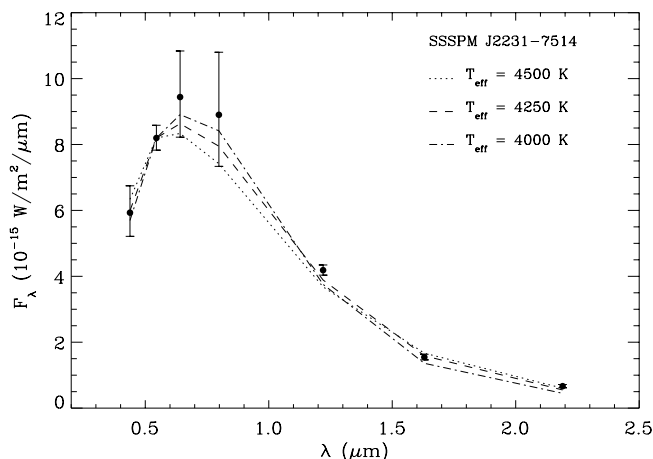

Fig. 1.—Cool hydrogen atmosphere model fits to the spectral energy distribution of SSSPM J2231−7514, assuming $\log g = 8.0$ (§ 2.3).
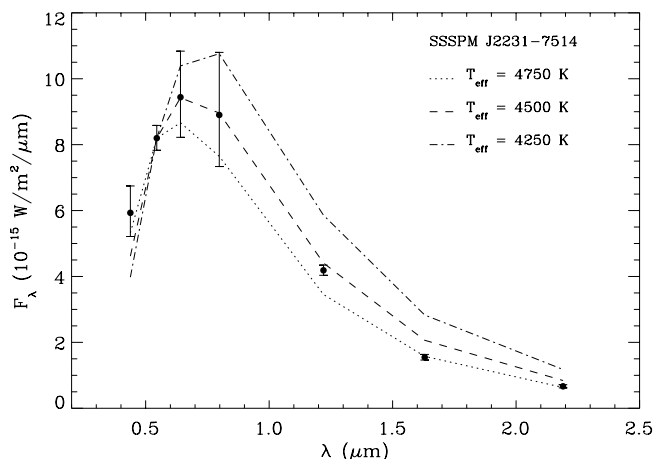

Fig. 3.—Cool helium atmosphere model fits to the spectral energy distribution of SSSPM J2231−7514, assuming $\log g = 8.0$ (§ 2.3).
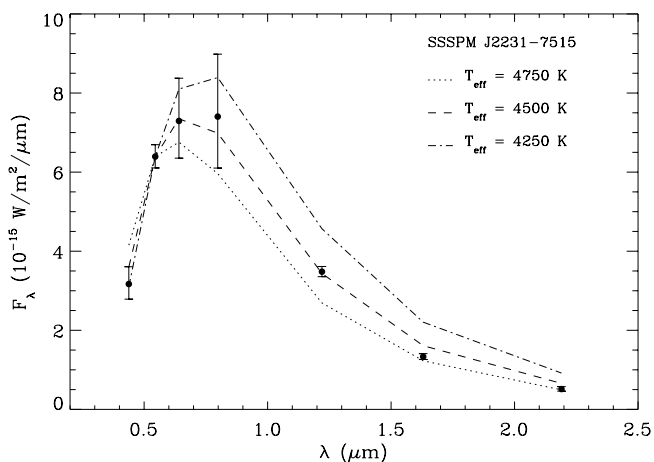
Fig. 4.—Cool helium atmosphere model fits to the spectral energy distribution of SSSPM J2231−7515, assuming $\log g = 8.0$ (§ 2.3).

Oppenheimer et al. 2001b). If all the data points are weighted equally, then a pure helium model is applicable, yielding $T_{eff} \approx 4500$ K for both stars (Figs. 3 and 4).

The fact that the data on both stars agree quite well with models of the same T_{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 ΔV, as could a ~ 200 K difference in T_{eff} (Bergeron et al. 1995b).

3. DISCUSSION

3.1. Ultracool White Dwarf Candidates

There are only four white dwarfs with published optical and near-infrared data supporting their status as $T_{eff} < 4000$ K degenerates. These ultracool white dwarfs are, in order of their discovery, LHS 3250, WD 0346+246, SDSS 1337+00, and GD 392B (Harris et al. 1999, 2001; Hodgkin et al. 2000; 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, 2001b; Ruiz & Bergeron 2001; Salim et al. 2004), and the five new Sloan stars recently reported by Gates et al. (2004).

Near-infrared photometry indicates that the proper motion–selected white dwarfs SSSPM J2231−7514 and SSSPM J2231−7515 both have $T_{eff} \gtrsim 4250$ 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 $T_{eff} < 4500$ K, as determined by full spectroscopic and photometric analyses including near-infrared data: LHS 239 and ER 8 (Bergeron et al. 1997, 2001; Holberg et al. 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 and 3600 K, respectively (Scholz et al. 2002). The analysis here

shows that 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 $T_{eff} = 3750$ K, as determined by parallax and total integrated flux (Hambly et al. 1997; Hodgkin et al. 2000; Oppenheimer et al. 2001b). 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_{eff} for cool white dwarfs.

The flux-calibrated optical spectra of F351-50 and F821-07 (LHS 542) were fitted with 3500 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 ~ 9000 Å (Hambly et al. 1997; Hodgkin et al. 2000; Oppenheimer et al. 2001b). Second, the most reliable effective temperature determination of LHS 542 is 4720 K, based on its trigonometric parallax plus optical and near-infrared photometry (Leggett et al. 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. (2001b), appears to have a flatter slope than WD 0346+246 out to 10000 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 have 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 in the halo. Halo white dwarfs can be older than 10 Gyr; therefore, according to models, they have had enough time to cool to sub–4000 K temperatures, regardless of atmospheric composition and mass (Bergeron et al. 1995a; 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 et al. 1995a; Hansen 1999; Serenelli 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 et al. 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 ∼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 are 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 it is very strong, when it is evident in flux-calibrated optical or near-infrared spectra (Harris et al. 1999, 2001; Hodgkin et al. 2000; 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 ($T_{\rm eff} = 5400$ 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 $T_{\rm eff} \approx 4250$ K for both white dwarfs. This value should be considered preliminary, as higher signal-to-noise ratio 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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