INFRARED PHOTOMETRIC ANALYSIS OF WHITE DWARFS FROM THE TWO MICRON ALL SKY SURVEY AND THE SPITZER SPACE TELESCOPE

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ABSTRACT

We review the available near- and mid-infrared photometry for white dwarfs obtained from the Two Micron All Sky Survey (2MASS) and by the Spitzer Space Telescope. Both data sets have recently been used to seek white dwarfs with infrared excesses due to the presence of unresolved companions or circumstellar disks, and also to derive the atmospheric parameters of cool white dwarfs. We first attempt to evaluate the reliability of the 2MASS photometry by comparing it with an independent set of published JHK CIT magnitudes for 160 cool white dwarf stars, and also by comparing the data with the predictions of detailed model atmosphere calculations. The possibility of using 2MASS to identify unresolved M dwarf companions or circumstellar disks is then discussed. We also revisit the analysis of 46 binary candidates from Wachter et al. using the synthetic flux method and confirm the large near-infrared excesses in most objects. We perform a similar analysis by fitting Spitzer 4.5 and 8 μm photometric observations of white dwarfs with our grid of model atmospheres, and demonstrate the reliability of both the Spitzer data and the theoretical calculations up to 8 μm. Finally, we search for massive disks resulting from the merger of two white dwarfs in a 2MASS sample composed of 57 massive degenerates, and show that massive disks are uncommon in such stars.

Subject headings: binaries: general — infrared: stars — planetary systems: protoplanetary disks — stars: fundamental parameters — white dwarfs

Online material: machine-readable tables

1. INTRODUCTION

With the recent All Sky Data Release of the Two Micron All Sky Survey1 (2MASS), we are now able to retrieve near-infrared (NIR) J, H, and Ks magnitudes for more than a thousand white dwarfs that fall within the 2MASS detection limit. This database was used in several studies aimed at identifying new cool white dwarfs (e.g., de la Fuente Marcos & de la Fuente Marcos 2005) or circumstellar disks (Kilic et al. 2006a) and seeking binary candidates (Wachter et al. 2003; Holberg & Magargal 2005; Debes et al. 2005). In the latter case, one of the main interests are the binary systems containing a main-sequence star and a white dwarf. These systems might reveal important details about stellar populations and evolution. Different techniques have been used to seek these binary candidates. Until recently, most systematic searches were based on surveys of resolved common-proper-motion binaries (Silvestri et al. 2002), but new interest has emerged for identifying unresolved binaries. One of the reasons is that accretion from a previously unknown close companion could account for the high metal abundances observed in some white dwarfs. The preferred method for seeking unresolved binary candidates is to perform a photometric analysis. In the case where the companion is an M dwarf, the white dwarf star usually dominates the observed flux in the optical regions. Therefore, it is natural to look for an excess in the NIR, either photometrically or spectroscopically, where the contribution from the M dwarf becomes dominant (see Dobbie et al. 2005 for a review).

Exploiting the 2MASS photometric data, different methods of analysis were used to identify NIR excesses. Wachter et al. (2003) used the second incremental 2MASS data release, which covers about 50% of the sky. The authors took the approach of a (J − H, H − Ks) two-color diagram for 795 white dwarfs recovered from the 2MASS survey. They identified 95 binary candidates, including 47 objects with prior evidence of binarity. They also suggested 15 additional tentative binary candidates. Wellhouse et al. (2005) used a similar two-color diagram approach with a sample of 51 magnetic white dwarfs as candidates for potential precataclysmic variables. While they did not find any binary candidates, they identified 10 objects with peculiar colors associated with very low mass companions or debris. Holberg & Magargal (2005) used the final 2MASS All Sky Data Release to study the 347 DA stars from the Palomar-Green survey (Liebert et al. 2005). Their technique relies on the spectroscopic determinations of effective temperature and surface gravity, which combined with the observed V magnitude, can be used to compare magnitudes predicted at J, H, and Ks with those available in the 2MASS Point Source Catalog (PSC). The same technique had been used before by Zuckerman & Becklin (1992) and Green et al. (2000), but with independent NIR photometric data sets. The disadvantage of this technique is that reliable atmospheric parameters and V magnitudes must be available for each star.

As the low-mass main-sequence companion gets cooler—typical of late-type M or L dwarfs—only a mild NIR excess is observed. The NIR excesses expected from circumstellar dust disks and planets around white dwarfs could be even less significant. Zuckerman & Becklin (1987) were the first to identify such a system for the 0.7 M⊙ DA7 star G29-38 (2326+049), also a ZZ Ceti pulsator. More recently, Kilic et al. (2005) and Becklin et al. (2005) went through a detailed analysis of GD 362 (1729+371), a massive DA7 star with unusually high metal abundances, some nearly solar (Gianninas et al. 2004). For both objects, there was a small but significant excess in the NIR that could be detected in the K band. However, it is from the large mid-infrared (MIR) excess (Reach et al. 2005; Becklin et al. 2005) that the disks could be confirmed. NIR spectroscopic observations and 2MASS data have also been used by Kilic et al. (2006a) to identify

1 See http://www.ipac.caltech.edu/2mass/releases/allsky.
a third DAZ white dwarf, GD 56, that could harbor a circumstellar disk, although this object has yet to be observed in the MIR. Chary et al. (1999) and Kilic et al. (2005, 2006a) analyzed a dozen other DA and DAZ stars and found no evidence for similar circumstellar disks. Jura (2003) discussed possible scenarios and concluded that not all white dwarfs with heavy elements in their atmospheres possess a dust disk similar to that of G29-38. The current picture is that as much as 14% of the DAZ stars host a circumstellar disk (Kilic et al. 2006a).

According to Livio et al. (2005) disks and planets could also result from the merger of two white dwarfs. Hence, the high-mass tail of the white dwarf mass distribution (see, e.g., Liebert et al. 2005) would represent the most promising candidates to search for such disks or planets. Livio et al. suggest that a typical dust disk would have a mass and radius of \( M_d \sim 0.007 M_\odot \) and \( R_d \sim 1 \) AU, respectively. This is much larger and massive than the disk proposed for G29-38 (Jura 2003). Therefore, the predicted flux excess should be easily detected in the NIR (assuming a standard composition and geometry) and the 2MASS survey should provide a useful tool to further constrain the proposed model.

In addition to the 2MASS NIR photometry, there is a developing interest to observe white dwarfs at longer wavelengths in the MIR. The Spitzer Space Telescope IRAC\(^2\) photometry and IRS infrared spectroscopy have been used in recent surveys of relatively bright, nearby white dwarfs to better constrain the atmospheric parameters of cool white dwarfs (Kilic et al. 2006b) and to seek MIR excesses from disks (Reach et al. 2005; Hansen et al. 2006). Since the contribution of a cold disk becomes dominant only in the MIR, the Spitzer data set is more sensitive to search for disks than the NIR 2MASS data set.

Before undertaking a more systematic search of white dwarf stars in binaries or of circumstellar disk systems using 2MASS or Spitzer data, it seems appropriate as a first step to evaluate properly the reliability of the infrared photometric data sets and the ability of current model atmospheres to reproduce the observations. We thus present in §2 a comparison of 2MASS photometry with published \( JHK \) magnitudes on the CIT photometric system for 160 cool white dwarfs, and assess the limitations of the 2MASS survey. We then evaluate in §3 the usefulness of the 2MASS photometric data for identifying binary candidates using various techniques, and discuss the implications of our results on several studies published in the literature. In §4 we perform a similar analysis, but using the Spitzer IRAC 4.5 and 8 \( \mu \)m photometry presented in Kilic et al. (2006b). Finally, in §5 we analyze a sample of 57 white dwarfs with spectroscopic masses above 0.8 \( M_\odot \) together with 2MASS photometry to search for disks around massive white dwarfs, such as those predicted by Livio et al. (2005). Our conclusions follow in §6.

### 2. COMPARISON OF CIT AND 2MASS PHOTOMETRY

Our photometric sample used to compare against the 2MASS data is drawn from the detailed photometric and spectroscopic analyses of Bergeron et al. (1997, hereafter BRL97), Leggett et al. (1998), and Bergeron et al. (2001, hereafter BLR01), who obtained improved atmospheric parameters of cool white dwarfs from a comparison of optical \( BVRI \) and infrared \( JHK \) photometry with the predictions of model atmospheres appropriate for these stars. We selected from these studies 183 cool white dwarfs with infrared \( JHK \) magnitudes measured on the CIT photometric system (with the exception of 0704–508, which has no \( K \) measurement). This sample covers a range of effective temperatures between \( T_{\text{eff}} \sim 4000 \) and 13,000 K, and all objects have been successfully fitted by BRL97 and BLR01 under the assumption of single stars (or double degenerates) with no evidence for any infrared excess that could be due to the presence of an unresolved low-mass main-sequence star.

We searched the 2MASS PSC for all white dwarfs in our sample using the GATOR batch file tool and a 20" search window centered on a set of improved coordinates measured by J. B. Holberg (2005, private communication). In most instances, multiple sources were found within the search window and we unambiguously identified each object by comparing the 2MASS atlas with the finding charts available from the online version of the Villanova White Dwarf Catalog.\(^3\) We recovered the 2MASS \( J \), \( H \), and \( K \) magnitudes for 160 stars from our initial CIT photometric sample of 183 objects. The remaining 23 objects were dropped from our analysis for the following reasons: 9 were too faint for the 2MASS survey, 11 were not properly resolved due to the presence of a nearby star, and 3 could not be unambiguously identified from the comparison of the 2MASS atlas and the published finding charts. Our final sample of 160 cool white dwarfs is presented in Table 1, where we provide the CIT and 2MASS magnitudes for each object. The uncertainties of the CIT magnitudes are 5% except where noted in Table 1, and the 2MASS photometric uncertainties are given in parentheses (magnitudes with null uncertainties represent lower limits).

Since the two data sets rely on completely different photometric systems, we must keep in mind that there could be a possible offset between both systems. For instance, Carpenter (2001) have obtained an empirical color transformation (see their eqs. [12]–[15]) based on a comparison of CIT and 2MASS photometry for 41 stars. However, since this transformation has been obtained in a broad general context and not specifically for cool

### Table 1

**Sample of Cool White Dwarfs with Near-Infrared Photometry**

| WD Name | CIT | 2MASS | 2MASS | CIT | 2MASS |
|---------|-----|-------|-------|-----|-------|
| WD Name | \( J \) | \( H \) | \( K \) | \( J \) | \( H \) | \( K \) |
| LHS 1008 | 14.17 | 14.02 | 13.87 | 14.117 (0.024) | 14.024 (0.038) | 13.919 (0.063) |
| LHS 1028 | 16.43 | 16.34 | 16.33 | 16.449 (0.128) | 16.193 (0.224) | 16.614 (null) |
| LHS 1038 | 13.41 | 13.26 | 13.21 | 13.490 (0.022) | 13.249 (0.026) | 13.191 (0.030) |
| G31-35 | 15.21 | 15.13 | 15.12 | 15.148 (0.039) | 15.214 (0.094) | 15.101 (0.139) |
| LHS 1044 | 14.85 | 14.62 | 14.52 | 14.813 (0.036) | 14.549 (0.057) | 14.628 (0.082) |

**Notes.**—CIT uncertainties are 5% except for the data marked ‘::’ or ‘::’, which indicate 10% and 20% uncertainties, respectively. 2MASS magnitudes with null uncertainties are lower limits. Table 1 is published in its entirety in the electronic edition of the Astrophysical Journal. A portion is shown here for guidance regarding its form and content.
INFRARED PHOTOMETRIC ANALYSIS OF WHITE DWARFS

We present in Table 2 a statistical comparison of both data sets for all three bands. The first three lines correspond to the full data set while the last three lines are restricted to 2MASS magnitudes that satisfy the level 1 requirements. The second column indicates the number of stars used for the comparison (to be included, the 2MASS magnitude must have a measurement error). The third and fourth columns represent respectively the mean and the standard deviation of the magnitude differences for each band. These mean values thus correspond to the zero point offsets between both photometric systems, and we therefore adopt the following transformation based on the most accurate subsample (level 1): $J_{\text{CIT}} = J_{\text{2MASS}} - 0.0083, H_{\text{CIT}} = H_{\text{2MASS}} + 0.0094$, and $K_{\text{CIT}} = K_{\text{2MASS}} + 0.0133$. We note that the offsets are typically 5 times smaller than the average 2MASS uncertainties—given in the fifth column of Table 2, $(\sigma_{\text{2MASS}})$—and these could as well be considered as zero for most practical purposes. We also note that since the effective wavelength of the 2MASS $K_s$ filter (2.169 μm) is slightly shorter than that of the CIT $K$ filter (2.216 μm), the observed flux should be larger at $K_s$ than at $K$, and a larger positive offset is thus expected for this band, as is indeed observed in Table 2.

If the uncertainties of both data sets have been properly evaluated, the average combined quadratic uncertainties, $(\sigma)$ (last column of Table 2), should be at least as large as the standard deviations of the magnitude differences (fourth column of Table 2). This is certainly the case for the level 1 subsample, a result that confirms the reliability of the 2MASS level 1 photometry. For the complete sample, however, the $(\sigma)$ values are slightly below the standard deviations. If we assume that the CIT photometric uncertainties have been properly estimated, which is supported in BRL97 and BLR01 by the successful fits with white dwarf models, the 2MASS uncertainties might be slightly underestimated in the case of faint cool white dwarfs near the survey limit. Another way of interpreting these results is to note that in Figure 1, the magnitudes are not compatible within the 1 $\sigma$ combined uncertainties for 34.6%, 30.6%, and 35.0% of the stars in the complete sample at the $J$, $H$, and $K$ bands, respectively. These correspond to the objects whose error bars do not cross the horizontal dashed lines. This occurs for level 1 and fainter objects as well. At a 3 $\sigma$ level, these numbers drop to 0.6%, 1.9%, and 4.2%, respectively, which suggests that there are infrequent but large discrepancies at $K_s$.

In Figure 2 we compare $(J - H, H - K/K_s)$ two-color diagrams for various data sets. In the top panels, we compare the two-color diagrams for the 143 stars in common in both the CIT and the 2MASS samples that have been detected by 2MASS in all three bands. The 2MASS colors appear much more scattered than the CIT colors, and this simply reflects the larger uncertainties of the

![Figure 1](image-url)

**FIG. 1.—** Differences in magnitudes between the infrared CIT and 2MASS photometric systems for each individual filter as a function of the 2MASS magnitude for our common sample of 160 cool white dwarfs. The error bars represent the combined quadratic uncertainties of both photometric data sets. The horizontal dotted lines indicate the mean magnitude differences between both data sets. Objects located on the left side of the vertical dotted lines meet the PSC level 1 requirements $(S/N > 10)$, which correspond to $J < 15.8$, $H < 15.1$, and $K < 14.3$. The 10 objects represented by open circles are discussed in the text and in Fig. 3.

**TABLE 2**

| Bandpass | Number of Stars | Mean | Standard Deviation | $(\sigma_{\text{2MASS}})$ | $(\sigma)^a$ |
|----------|-----------------|------|--------------------|---------------------------|--------------|
| $J_{\text{CIT}} - J_{\text{2MASS}}$ | 159 | -0.0046 | 0.0805 | 0.0502 | 0.0745 |
| $H_{\text{CIT}} - H_{\text{2MASS}}$ | 157 | +0.0180 | 0.1126 | 0.0807 | 0.0997 |
| $K_{\text{CIT}} - K_{\text{2MASS}}$ | 143 | +0.0247 | 0.1561 | 0.1096 | 0.1255 |
| $J_{\text{CIT}} - J_{\text{2MASS}} (S/N > 10)$ | 130 | -0.0083 | 0.0679 | 0.0409 | 0.0662 |
| $H_{\text{CIT}} - H_{\text{2MASS}} (S/N > 10)$ | 97 | +0.0094 | 0.0675 | 0.0502 | 0.0726 |
| $K_{\text{CIT}} - K_{\text{2MASS}} (S/N > 10)$ | 49 | +0.0133 | 0.0692 | 0.0466 | 0.0697 |

*a Average value of $\sigma$ where for a single star, $\sigma = (\sigma_{\text{2MASS}}^2 + \sigma_{\text{CIT}}^2)^{1/2}$. 

white dwarfs, we first compare directly both photometric data sets without any transformation, and discuss the possible offsets in the present context.

Figure 1 shows the differences in magnitudes between the infrared CIT and 2MASS photometric systems for the $J$, $H$, and $K/K_s$ filters for the white dwarfs from Table 1. Note that the number of stars in each panel is different (159 in $J$, 157 in $H$, and 143 in $K_s$) since some stars have not been formally detected in one or more bands, and lower limits are available. The size of the error bars in Figure 1 correspond to the combined quadratic uncertainties of both data sets, $\sigma = (\sigma_{\text{2MASS}}^2 + \sigma_{\text{CIT}}^2)^{1/2}$. For both measurements to be compatible, the error bar must touch the horizontal dashed line in each panel of Figure 1, which represents the mean magnitude difference between both data sets, as determined below.
former data set. Indeed, if we restrict the sample to the 49 objects that satisfy the level 1 requirements, the scatter of the 2MASS diagram is greatly reduced, as shown in the bottom panels of Figure 2. For this restricted sample, both CIT and 2MASS data appear to have a similar scatter, which is a confirmation of the comparable mean uncertainties. Since the 2MASS photometry has been used to infer the presence of unresolved white dwarf and low-mass main-sequence binaries, one needs to be cautious when interpreting data sets that include objects below the level 1 requirements.

For instance, we indicate by open circles in Figures 1 and 2 10 objects whose optical $BVRI$ and infrared $JHK$ photometry on the CIT system has been successfully fitted with single white dwarf models by BRL97 and BLR01. They cover a range in 2MASS $J$ magnitudes from 13.5 to 17. Our best fits for these stars are displayed in Figure 3. The fitting technique used here is described at length in BRL97. Briefly, the magnitudes on the CIT system in Table 1 are first transformed onto the Johnson-Glass system using the transformation equations given by Leggett (1992). These magnitudes are then converted into observed fluxes using the method described by Holberg & Bergeron (2006) for photon-counting devices but using the transmission functions taken from Bessell (1990) for the $BVRI$ filters on the Johnson-Cousins photometric system, and from Bessell & Brett (1988) for the $JHK$ filters on the Johnson-Glass system. The resulting energy distributions are then compared with those predicted from our model atmosphere calculations, properly averaged over the same filter bandpasses. The hydrogen- and helium-rich model atmospheres used in our analysis are similar to those described in BLR01 and references therein, except that for the hydrogen-rich models we are now making use of the more recent H$_2$-H$_2$ collision-induced opacity calculations of Borysow et al. (2001) and the Hummer-Mihalas occupation probability formalism for all species in the plasma. We find that the differences in the fitted parameters are small compared to those derived by BLR01, however.

![Figure 2](image-url)

Fig. 2.—Top: $(J − H)$ vs. $(H − K/K)$ two-color diagrams for 143 cool white dwarfs taken from Table 1 and detected by 2MASS in all three bands. The left and right panels correspond to the CIT and 2MASS magnitudes, respectively. The error bars indicate the mean uncertainties of each data set. Bottom: Same as top, but for the 49 white dwarfs satisfying the level 1 requirements. The region above the dashed line and that defined by the dotted rectangle correspond to the color criteria defined by Wachter et al. (2003) for selecting binary candidates and tentative binary candidates, respectively. The 10 objects shown by open circles are discussed in the text and in Fig. 3.
The effective temperature $T_{\text{eff}}$, the solid angle $\pi (R/D)^2$ (with $R$ the radius of the star and $D$ its distance from Earth), and the atmospheric composition (H- or He-rich) are obtained through a minimization technique, where the $\chi^2$ value is taken as the sum over all bandpasses of the difference between observed and predicted fluxes, properly weighted by observational uncertainties. The trigonometric parallax measurement, when available, is used to constrain the surface gravity through the mass-radius relation for white dwarfs; otherwise a value of $\log g = 8.0$ is assumed. In Figure 3 the observed $BVRJHK$ fluxes are shown as error bars together with the monochromatic model fluxes (for clarity, we do not show the average model fluxes at each bandpass). The derived atmospheric parameters are given in each panel. As can be seen, the energy distributions for all objects can be successfully reproduced by assuming a single-star model.

Also reproduced in Figure 3 are the 2MASS magnitudes converted into fluxes using the 2MASS zero points of Holberg & Bergeron (2006). We note that for 9 of the 10 objects, at least one of the fluxes at $J$, $H$, or $K_s$ is not compatible with the predicted fluxes within the $1 \sigma$ 2MASS uncertainties. One exception is...
0029-032, discussed later in § 3, for which the model spectrum matches the 2MASS photometry even better than the CIT photometry. We thus conclude this section by stating that while the 2MASS photometry is generally reliable, one should expect occasional discrepancies. In particular, the detailed fits (not shown here) to the energy distributions using the 2MASS photometry are of good quality for most stars in our sample.

3. WHITE DWARFS AND LOW-MASS MAIN-SEQUENCE BINARIES FROM 2MASS

3.1. The Wachter et al. Analysis

One of the most immediate applications to a large data set of white dwarf NIR photometry such as 2MASS is to seek infrared excesses due to cooler companions that are otherwise invisible in the optical. Wachter et al. (2003) used a sample of 759 white dwarfs from the catalog of McCook & Sion (1999) and identified as many as 95 binary candidates and 15 tentative binary candidates based on the analysis of a \((J - H, H - K_s)\) two-color diagram built from 2MASS photometry. They extracted \(JHK_s\) magnitudes from the 2MASS second incremental data release. Their binary candidates were selected from the color criterion \((J - H) > 0.4\), defined by the dashed horizontal lines in our Figure 2, while their 15 tentative binary candidates satisfy the criterion \(0.2 < (H - K_s) < 0.5\) and \(0.1 < (J - H) < 0.4\), defined by the dotted rectangles in Figure 2. In the following, we use the 2MASS final data release to recover more precise and slightly different observed \(JHK_s\) magnitudes than those reported by Wachter et al.

Using the same color criteria to study the 2MASS sample of presumably single cool white dwarfs presented in § 2, we find in the top right panel of Figure 2 several binary and tentative binary candidates in both regions defined by Wachter et al. (2003). A comparison with the CIT photometry, however, reveals that this result can be readily explained in terms of the larger uncertainties of the 2MASS photometry since both regions are located 1–2 \(\sigma\) away from the region occupied by single white dwarfs near the center of the figure. We find that 3.5% and 8.4% of our sample observed by 2MASS contaminate the binary candidate and tentative binary candidate regions, respectively. By comparison, we find that at least 12.5% of the white dwarfs in the complete sample of 759 objects of Wachter et al. are located in the binary candidate region. This indicates that the color criterion defined to identify companions is certainly appropriate, but also that the contamination from faint objects with large uncertainties near the 2MASS detection threshold may be significant. Furthermore, our large contamination of the tentative binary candidate region suggests that this criterion is not stringent enough, and that the corresponding subsample identified by Wachter et al. (2003, Table 2) is mostly composed of single white dwarfs.

These conclusions are supported by the fact that one of the objects selected in the list of binary candidates (0102+210B) and four objects in the list of tentative binary candidates (0029–032, 0518+333, 0816+387, and 1247+550) are all part of the single white dwarf sample described in § 2 and whose fits are displayed in Figure 3. As can be seen, the CIT photometry for all objects is well reproduced with single-star model atmospheres. For 0029–032, our fit is even better using the 2MASS photometry than the CIT data. For the other stars, the 2MASS energy distributions appear flatter than those inferred from the CIT photometry or the model spectra, a result that could be interpreted as a flux excess in the \(K\) band.

3.2. The Wellhouse et al. Analysis

Using a similar approach but with slightly different criteria, Wellhouse et al. (2005) sought companions to 51 magnetic white dwarfs as candidates for potential precataclysmic variables. They proposed to split the \((J - H, H - K_s)\) two-color diagram into four regions delimiting (I) single white dwarfs, (II) main-sequence binary candidates, (III) white dwarfs with very low mass companions, and (IV) objects that may be contaminated by circumstellar material. These representative regions are divided according to previous findings by Wachter et al. (2003) as well as theoretical color simulations. While they did not find any convincing binary candidates (region II), Wellhouse et al. identified six objects with a possible very low mass companion (region III) and four white dwarf candidates with an excess at \(K_s\) (region IV), which they interpreted as a signature of undetected planetary nebulae. This represents a total of 28.6% of their sample with formal uncertainties with a possible companion or a disk.

The four regions defined by Wellhouse et al. (2005) are reproduced here in the \((J - H, H - K_s)\) two-color diagram shown in Figure 4, together with our common sample of CIT and 2MASS data composed of presumably single white dwarfs. From this figure, we find that 21% of the white dwarfs in the 2MASS data set would be considered possible candidates for a companion or a disk, while the CIT data show little evidence for such infrared excesses. This strongly suggests that the sample of magnetic white dwarfs studied by Wellhouse et al. could be entirely consistent with single stars. In addition, we note that among the six objects located in region III of Figure 1 of Wellhouse et al. are some of the most intrinsically peculiar white dwarfs.

4 The actual percentage may be larger depending on how many faint objects with a partial detection are removed from the sample.

5 We also found that the 2MASS identification of 0145-174 by Wachter et al. is erroneous; the actual star is much fainter and not recovered in the 2MASS PSC.

6 Also, 2201–228 in that sample is probably not magnetic according to S. Jordan (2005, private communication).
has been reported by Schmidt et al. (1999) and it has the strongest C$_2$-like features ever observed, LP 790-29 (1036–204) is the strongest magnetic DQ known, and GD 229 (2010+310) shows strong unidentified absorption features in the optical (Wesemael et al. 1993, Fig. 19). Therefore, region III seems to be populated with some of the most peculiar white dwarfs for which there is no reason to expect their NIR colors to overlap with those of normal white dwarfs. Similarly, if we restrict our analysis to the more accurate CIT data, there are three white dwarfs located in region III of our Figure 4. Two of these identified in the figure are also peculiar: G240-72 (1748+708) shows a deep yellow sag in the 4400–6300 Å region (Wesemael et al. 1993, Fig. 19), and LP 701–29 (2251–070) is a heavily blanketed DZ star (Wesemael et al. 1993, Fig. 11).

We also note that all four objects in region IV of Wellhouse et al. (2005, Fig. 1) are very faint stars with 2MASS $K_s$ uncertainties in the range 0.16–0.27. As seen in our Figure 4, we do expect single white dwarfs with large uncertainties to populate this particular region as well. Hence the location of the four objects identified by Wellhouse et al. in this particular region of the $(J - H, H - K_s)$ two-color diagram is most naturally explained in terms of the low quality of the 2MASS data for these objects rather than the presence of planetary nebulae. We thus conclude that the identification of NIR excesses in the 2MASS PSC database requires more conservative criteria allowing for larger uncertainties in the photometric measurements below the level 1 requirements, or more accurate methods such as that presented in the following section.

### 3.3. The Synthetic Flux Method

Another technique for identifying binary candidates is to compare observed 2MASS fluxes directly with those predicted from model atmospheres (see, e.g., Holberg & Magargal 2005; Holberg & Bergeron 2006). Effective temperatures and surface gravities are first obtained using the spectroscopic method developed by Bergeron et al. (1992), where high signal-to-noise spectroscopic observations of the hydrogen Balmer lines are fitted with synthetic models. The model flux is then normalized to the observed $V$ magnitude to predict the observed fluxes at $J$, $H$, and $K_s$ using the 2MASS filter passbands from Cohen et al. (2003) and the zero points from Holberg & Bergeron (2006). Thus, only objects with known atmospheric parameters and $V$ magnitudes can be used with this method. In what follows, we rely on the fitting technique and NLTE model atmospheres for DA stars described in Liebert et al. (2005) and references therein.

To illustrate the method, we selected all DA stars from Wachter et al. (2003) for which we had an optical spectrum and a published $V$ magnitude. In Table 3 we present our sample that includes 42 binary candidates and 5 tentative binary candidates from Tables 1 and 2, respectively, of Wachter et al. (2003). For each object, we give the atmospheric parameters ($T_{\text{eff}}$ and $\log g$), the published $V$ magnitude, and the predicted and observed 2MASS magnitudes at $J$, $H$, and $K_s$. In some cases, the optical spectrum was significantly contaminated by the unresolved companion, and the uncertainties on the derived parameters are correspondingly larger; these are indicated by colons in Table 3.

For most objects, a significant NIR excess is observed, with the 2MASS data being typically $\sim 2$ mag brighter than the values predicted from the model fits. In Figure 5 we present typical results for 10 objects selected from Table 3. Here we show the observed 2MASS fluxes together with the predicted monochromatic fluxes calculated at the atmospheric parameters given in each panel. For 0023+388, 0034−211, 0131−163, and 0145−257, the companion can be unambiguously detected since the 2MASS fluxes are about a factor of 10–100 larger than the predicted fluxes. For 0145−221, only a mild NIR excess is observed and this object has indeed been identified as a WD+dL6/7 by Farihi et al. (2005) and Dobbie et al. (2005). Two of the tentative binary candidates, 0710+741 and 2257+162, do indeed show a significant excess consistent with a very low mass companion. Farihi et al. (2005) have actually confirmed that 0710+741 is a WD+dM7. However, for 1434+289, 1639+153, and 2336−187, which are tentative binary candidates in Wachter et al. (2003), we do not observe any significant NIR excess and these objects are thus consistent with being single white dwarfs.

With the exception of these last three objects, the infrared excesses observed in Table 3 are consistent with unresolved low-mass main-sequence M dwarfs physically associated with the white dwarfs (Farihi et al. 2006). Photometric observations of single M dwarfs by Leggett et al. (1996) show that the $(J - V)$ color index is in the range from $\sim 2$ to 4, while single cool white dwarfs are expected to be in the range from $\sim 1$ to 1. This explains why the contribution of the M dwarf can be dominant in the NIR but negligible in the optical. Many of the 44 remaining binary candidates in Table 3 have been discussed in the literature. For instance, Farihi et al. (2005) and Farihi et al. (2006) with HST observed 28 candidates from this list and were able to resolve the red dwarf companion(s) for 17 objects. The NIR excesses were also confirmed by Farihi et al. (2005, 2006) using $JHK$ photometric observations for the 11 remaining unresolved objects. The

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**Table 3**

Sample of White Dwarfs with Predicted NIR Photometry

| WD      | $T_{\text{eff}}$ (K) | $\log g$ | $V$ | $J_{\text{pred}}$ | $H_{\text{pred}}$ | $K_{s\text{ pred}}$ | $J_{2\text{MASS}} (\sigma_V)$ | $H_{2\text{MASS}} (\sigma_V)$ | $K_{2\text{MASS}} (\sigma_V)$ |
|---------|----------------------|----------|-----|-------------------|-------------------|---------------------|-------------------------------|-------------------------------|-------------------------------|
| 0023+388| 10785                | 8.14     | 15.97 | 15.988            | 15.979            | 16.121              | 13.810 (0.026)               | 13.268 (0.030)               | 12.939 (0.033)               |
| 0034−211| 17217                | 8.04     | 14.53 | 14.934            | 15.000            | 15.161              | 14.504 (0.020)               | 13.868 (0.021)               | 12.638 (0.026)               |
| 0131−163| 49042                | 7.81     | 13.96 | 14.667            | 14.808            | 15.000              | 12.966 (0.027)               | 12.468 (0.028)               | 12.215 (0.030)               |
| 0145−257| 25635                | 7.97     | 14.51 | 15.089            | 15.200            | 15.382              | 11.830 (0.021)               | 11.594 (0.023)               | 11.594 (0.023)               |
| 0145−221| 11549                | 8.14     | 14.85 | 14.965            | 14.974            | 15.122              | 14.923 (0.032)               | 14.450 (0.045)               | 14.335 (0.064)               |

Notes.—Uncertainties of the atmospheric parameters are 1.2% in $T_{\text{eff}}$ and 0.038 dex in $\log g$. The $V$ magnitudes are from various sources in the literature. The objects marked with a colon are contaminated by the companion in the visible and the uncertainties are correspondingly larger. Table 3 is published in its entirety in the electronic edition of the *Astrophysical Journal*. A portion is shown here for guidance regarding its form and content.

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7 Note that the 2MASS identification for 40 Eri B (0413+077) by Wachter et al. is erroneous. With two objects within $2^\circ$, they picked what is probably the M dwarf 40 Eri C instead of 40 Eri B itself. Thus, while this is still technically a WD+dM binary, both objects are barely resolved in 2MASS and we do not include them in our sample.
The presence of a companion for nine additional objects in Table 3 has been discussed at various degrees in the literature, while for the seven remaining binary candidates (0812+478, 0915+201, 1037+512, 1108+325, 1339+346, 1610+383, and 2257+162), we confirm through the synthetic flux method a strong NIR excess consistent with the presence of low-mass main-sequence companions.

We have seen that for a brown dwarf companion, the flux excess is not as important as for M dwarfs. In the case of the dL6/7 dwarf companion to 0145−221, the flux excess at $K_s$ is still significant at the 12σ level, however, according to Table 3. There is only one known example of a companion with a possible later spectral type, the brown dwarf companion to 0137−349, discovered from radial velocity measurements by Maxted et al. (2006), who also report a small excess at $K_s$ from 2MASS PSC data. Burleigh et al. (2006) also present a near-IR spectrum that confirms the slight $K$-band excess they attribute to a dL8 companion.

We analyzed the 2MASS photometry of this object with the method described in this section, and assumed the effective temperature and surface gravity from Maxted et al. (2006). We were able to match very well the predicted and observed 2MASS $J$ magnitude.

Fig. 5.—Observed 2MASS fluxes (error bars) for several binary and tentative binary candidates from Wachter et al. (2003) compared with the predictions of model atmospheres (solid lines) normalized at $V$. The atmospheric parameters derived from the spectroscopic method are given in each panel.
within the uncertainties, and also identified a flux excess at $K_s$ at the 2.49 $\sigma$ level, which is barely significant, but still consistent with the presence of a disk or a companion. Therefore, the 2MASS survey is able to identify hot brown dwarf companions, but it becomes more difficult to confirm their presence for spectral types later than about dL7.

We end this section by asserting that methods based on comparisons of observed and predicted 2MASS fluxes (or magnitudes) represent an efficient way of identifying unresolved white dwarf and low-mass main-sequence binaries down to late-type L dwarfs. Our analysis also reveals, however, that $(J - H, H - K_s)$ two-color diagrams based on 2MASS data should be interpreted with caution, and that regions expected to contain unresolved binaries may be contaminated with single white dwarfs, especially when data below the level 1 requirements are considered.

4. INFRARED PHOTOMETRY FROM SPITZER

The Spitzer Space Telescope has been used to secure for the first time IRAC 4.5 and 8 $\mu$m photometric data for relatively bright, nearby white dwarfs (see, e.g., Hansen et al. 2006). One of the main interests of these surveys is to look for infrared flux excesses due to the presence of circumstellar disks since it is expected that the cool disk would dominate the MIR flux. It is however necessary as a first step to evaluate the reliability of the Spitzer data set and the ability of the model atmospheres to reproduce the MIR fluxes. In such an effort, Kilic et al. (2006b) compared the Spitzer 4.5 and 8 $\mu$m photometric data of 18 cool and bright white dwarfs with the predictions of model atmospheres. They found that the four hydrogen atmosphere white dwarfs with $T_{\text{eff}} \lesssim 6000$ K show a slight flux depression at 8 $\mu$m, while one peculiar object, the so-called C$_2$H star LHS 1126, suffers from a significant flux deficit at both 4.5 and 8 $\mu$m. For the warmer objects, the model fluxes seem to reproduce the Spitzer data perfectly.

In this section, we reanalyze 14 objects from the sample of Kilic et al. (2006b) for which optical BVRI photometry and infrared JHK photometry on the CIT system are available (all of these are already part of our cool white dwarf sample discussed in § 2). In an approach similar to that described in § 2 (see Fig. 3), we determine the atmospheric parameters for each star by fitting simultaneously the average fluxes for the nine photometric bands (BVRI, JHK/CIT, and Spitzer 4.5 and 8 $\mu$m). The synthetic fluxes in the MIR are obtained by integrating our model grid over the Spitzer IRAC spectral response curves while the observed fluxes are taken directly from Table 1 of Kilic et al. (2006b). In contrast with the technique used by Kilic et al., we do not normalize the fluxes at any particular band, but consider instead the solid angle $\pi(R/D)^2$ a free parameter. Since our $\chi^2$ value is taken as the sum over all bands of the difference between observed and model fluxes, properly weighted by the corresponding observational errors, our approach has the advantage of allowing for the full photometric uncertainties in the fitting procedure. Furthermore, instead of assuming log $g = 8.0$ for all objects, we constrain the log $g$ value from the trigonometric parallax measurements, as described above.

In Figure 6 we present our best fits on a logarithmic scale to the observed BVRI, JHK (CIT), and Spitzer photometry with the model average fluxes described above. We also plot the monochromatic fluxes for clarity; the case of LHS 1126 is discussed separately below. Another peculiar object, G240-72 (1748+$708$) already discussed near the end of § 3.2, shows a deep unidentified absorption in the optical (a yellow sag) and no satisfactory fit can be achieved for this star and it is thus left out of our analysis. For Ross 627 (1121+216), the 8 $\mu$m flux is not shown in Figure 6 since Kilic et al. (2006b) provides only an upper limit due to a possible contamination from a nearby star. Our final sample thus includes 12 stars with 23 Spitzer 4.5 and 8 $\mu$m flux measurements. For all cases shown in Figure 6, the Spitzer fluxes are well reproduced by the synthetic models. To further strengthen this conclusion, we plot in Figure 7 the ratio of the observed to model fluxes at 4.5 and 8 $\mu$m as a function of the derived effective temperature for the 12 objects. The figure confirms the agreement between the observed Spitzer and model fluxes at all temperatures. In particular, we do not observe any significant flux deficit at low effective temperatures as suggested by Kilic et al. (2006b). There are only 2 observations out of 23 for which the flux deficit is significant at the 1 $\sigma$ level, and both are in the 8 $\mu$m band. It thus seems premature to conclude from these results that there is any discrepancy between the observations and the predictions of model atmospheres with pure hydrogen compositions.

We mention in this context that the second coolest object in Figure 7 is the DA star BPM 4729 (0752+767), for which we obtain a perfect fit. This star has been studied extensively by BLR01, and more recently by Kowalski & Saumon (2006) using improved L$_\alpha$ profiles that include broadening by molecular hydrogen, and both atmospheric parameter determinations agree at the 1 $\sigma$ level under the assumption of pure hydrogen compositions. Hence for
Another white dwarf analyzed by Kilic et al. (2006b) is LHS 1126 (0038 – 226), whose energy distribution is characterized by a strong infrared flux deficiency at JHK interpreted by Bergeron et al. (1994) in terms of collision-induced absorption (CIA) by molecular hydrogen due to collisions with helium in a mixed hydrogen and helium atmosphere with N(H)/N(He) ~ 0.01. We do confirm here the results shown in Figure 4 of Kilic et al. (2006b) where the Spitzer fluxes are significantly depressed with respect to the predictions of model atmospheres with mixed compositions. The main reason for this discrepancy is that the CIA opacity predicts a maximum absorption near the H2 fundamental vibration frequency at ~2.4 μm, while the Spitzer fluxes are more consistent with a featureless energy distribution from 1 to 8 μm. This problem is surprisingly similar to that encountered in the so-called ultracool white dwarfs, and in particular in the case of LHS 3250 for which the H2-H2 and H2-He CIA opacities predict absorption bands that are simply not observed in spectroscopy (Bergeron & Leggett 2002). These results may indicate that the collision-induced opacity calculations need to be improved at the high densities encountered in cool white dwarf atmospheres.

5. CANDIDATE WHITE DWARFS WITH CIRCUMSTELLAR DISKS

The synthetic flux method based on a comparison of predicted and observed 2MASS fluxes (or magnitudes) was shown to be an efficient technique for detecting NIR excesses from unresolved companions (§3). However, the NIR excess in the JHK bands expected from cool circumstellar disks or planets surrounding white dwarf stars can be extremely small if the flux is dominated by the white dwarf in this particular wavelength range. In this section, we use the results of the ongoing spectroscopic survey of Gianninas et al. (2006) together with the 2MASS PSC to search for massive disks resulting from the merger of two white dwarfs, as predicted by Livio et al. (2005). In addition to the synthetic flux method described above, we also compare the observed and predicted (J – H) and (J – Ks) color indices since this method has the advantage of being independent of the normalization at V, which allows us to consider also objects with no published V magnitudes. Since circumstellar disks are expected to be much brighter at Ks than in the other bands, we expect their color indices to be very different from those of single white dwarfs, and such objects should easily stand out in our analysis.

As discussed in §1, white dwarfs resulting from mergers are expected to be found in the high-mass tail of the mass distribution. We thus selected all DA stars from the survey of Gianninas et al. (2006) with spectroscopic masses above 0.8 Msun, that were formally detected by 2MASS in at least two bands (usually the J and H bands), for a total of 57 objects. In Table 4 we provide the effective temperature, the spectroscopic mass, the V magnitude (when available), as well as the predicted and observed 2MASS JHK magnitudes for each object in our sample. The atmospheric parameters (Teff and log g) are obtained from fits to the Balmer lines using the NLTE model grid described in §3, and the log g values are converted into mass using the evolutionary models of Wood (1995) with carbon-core compositions and thick hydrogen layers. The predicted fluxes are obtained from the synthetic flux method and are thus only given for objects with measured V magnitudes.

Five white dwarfs in Table 4 (0429+176, 0950+139, 1058–129, 1120+439, and 1711+668) show a large NIR flux excess that is not attributable to a circumstellar disk. The predicted spectra for these stars are shown in Figure 8 together with the observed 2MASS fluxes. We discuss each object in turn.
HZ 9 (0429+176).—This object is a WD+dM binary (Lanning & Pesch 1981) in common with the sample discussed in § 3.

PG 0950+139.—This star is in common with the sample discussed in § 3. The white dwarf is surrounded by a planetary nebula (Ellis et al. 1984) and its optical spectrum exhibits emission lines (Liebert et al. 1989). According to Fulbright & Liebert (1993) the low-density gas emission and the infrared excess are best explained by the presence of a low-mass companion.

PG 1058–129, PG 1120+439.—These two objects show a mild and unexplained infrared excess. In both cases, the only V magnitudes available are multichannel data from the Palomar-Green survey (Green et al. 1986). Since the observed energy slopes measured by color indices are in perfect agreement with those predicted by the models (see below), it is very likely that the V magnitudes for these stars are simply erroneous. We note that Green et al. (2000) also determined a 1 σ significant excess at J for PG 1120+439.

RE J1711+664 (1711+668).—This white dwarf is a barely resolved visual pair (Finley et al. 1997). The predicted NIR flux from this white dwarf is too low to be detected by 2MASS. Thus only the dM star ∼2″ away from the white dwarf is detected in the PSC.

We exclude from our analysis the three objects with known companions, but we keep PG 1058–129 and PG 1120+439.

We compare in Figure 9 the observed and predicted (J − H) and (H − Ks) color indices as a function of H and Ks, respectively, for the remaining 54 white dwarfs in our sample. An examination of these results indicate that all stars are consistent with the predicted white dwarf colors within 3 σ uncertainties, both above and below the level 1 requirements. Two glaring exceptions are G1-7 (0033+016) and CBS 413 (1554+322), which are among the faintest objects in the bottom panel of Figure 9 (labeled 1 and 2, respectively). For G1-7, however, the color indices derived from the CIT photometry given in Table 1 are in excellent agreement with those predicted by the models. Also, CBS 413 has not been detected at H but it is unexpectedly bright at Ks! Since this object has no published V magnitude, it is not clear whether the J detection is indeed from the white dwarf, and thus whether the color excess at Ks is even real. Therefore, we conclude from the results shown in Figure 9 that there is no strong evidence for H or Ks excesses in this sample of massive white dwarfs, and for the presence of massive circumstellar disks around them.

For comparison, we also reproduce in Figure 9 the location of three white dwarfs with previously identified circumstellar disks: G29-38 (2326+049), GD 362 (1729+371), and GD 56 (0408−041). The atmospheric parameters for all three stars have been determined using our own spectroscopic observations, and the predicted 2MASS color indices have been estimated from the same method as above. For the metal-rich DAZ star GD 362, we use the more accurate atmospheric parameters of Gianninas et al. (2004), who took into account the presence of heavy elements in their model atmosphere calculations. Only GD 362 in our sample is a massive white dwarf with $M = 1.24 M_\odot$, while we obtain $M = 0.70$ and $0.60 M_\odot$ for G29-38 and GD 56, respectively. The disk around G29-38 was the first discovered and studied extensively in the MIR (Reach et al. 2005). The object is clearly identifiable in Figure 9 with ($J − K_s$)$_{2MASS} − (J − K_s)^{pred} = 0.52 ± 0.04$, a ∼12 σ result. The second object, GD 362, is a massive DAZ star for which Becklin et al. (2005) reported the discovery of an important flux excess at L' (3.76 μm) and N' (11.3 μm). Kilic et al. (2005) obtained a near-infrared spectrum in the 0.8−2.5 μm range but found only a mild flux excess at K. Both studies concluded that the presence of a dust disk could account for the observations. Given that GD 362 is particularly faint ($V = 16.3$), only lower limits at H and Ks are available in the 2MASS PSC. Instead, we use in Figure 9 the JHK_s magnitudes measured by Becklin et al. (2005). With these measurements, GD 362 exhibits a color excess of ($J − K_s$)$_{2MASS} − (J − K_s)^{pred} = 0.22 ± 0.04$, a 5 σ result. Unfortunately, this photometric accuracy is only achieved in the 2MASS sample for $J$ brighter than ∼14.1, and a color excess of the magnitude found in GD 362 cannot be easily uncovered in the majority of white dwarfs detected by 2MASS. For GD 56, Kilic et al. (2006a) reported a NIR excess in both the 2MASS data and in their own infrared spectroscopic observations. Unlike the two previous objects, GD 56 lacks the MIR observations that could confirm the presence of a disk. We recovered the 2MASS magnitudes from the PSC and determined a color excess of ($J − K_s$)$_{2MASS} − (J − K_s)^{pred} = 0.54 ± 0.19$, a 2.9 σ result, barely significant according to our 3 σ criterion.

From the analysis of the three known white dwarfs with circumstellar disks, we conclude that the infrared excess from similar disks around white dwarfs would be significant only for bright level 1 2MASS objects. We argue that while the 2MASS PSC is indeed able to suggest the presence of a disk for fainter stars like GD 56, MIR photometric observations or more accurate NIR data would be required to unambiguously identify circumstellar disks such as those discussed here. Furthermore, according to Livio et al. (2005) a circumstellar disk resulting from the merger of two white dwarfs would presumably have a much larger mass and radius in comparison with the disks currently known. Hence the expected NIR excess should also be large. Obviously, such large infrared excesses have not been detected in our 2MASS sample, and we conclude that massive circumstellar disks are uncommon around massive white dwarfs, in agreement with the conclusions reached by Hansen et al. (2006) based on Spitzer data. While our results constrain the scenario proposed by Livio et al. (2005) the fraction of massive degenerates in our sample that

| WD          | $T_{\text{eff}}$ (K) | $M/M_\odot$ | $V$ | $J_{\text{pred}}$ | $H_{\text{pred}}$ | $K_{\text{pred}}$ | $J_{2MASS} (\sigma_J)$ | $H_{2MASS} (\sigma_H)$ | $K_{2MASS} (\sigma_K)$ |
|-------------|---------------------|-------------|-----|-------------------|-------------------|-------------------|------------------------|------------------------|------------------------|
| 0033+016    | 10984               | 1.11        | 15.61| 15.638            | 15.632            | 15.679            | 15.650 (0.057)         | 15.522 (0.090)         | 16.119 (0.303)         |
| 0052+226    | 9652                | 1.05        | 16.16| 15.966            | 15.918            | 15.947            | 16.021 (0.077)         | 16.109 (0.162)         | 15.522 (0.212)         |
| 0052−147    | 25683               | 0.80        | 15.12| 15.715            | 15.832            | 15.912            | 15.724 (0.061)         | 15.532 (0.109)         | 15.457 (null)          |
| 0101+059    | 14191               | 0.83        | ... | ...               | ...               | ...               | 16.214 (0.089)         | 16.387 (0.210)         | 17.182 (null)          |
| 0143+216    | 9292                | 0.92        | 15.05| 14.792            | 14.732            | 14.755            | 14.784 (0.036)         | 14.812 (0.060)         | 14.676 (0.077)         |

Notes.—2MASS magnitudes with null uncertainties are lower limits. Mean uncertainties of effective temperatures and masses are 1.2% and 0.03 $M_\odot$, respectively. Table 4 is published in its entirety in the electronic edition of the Astrophysical Journal. A portion is shown here for guidance regarding its form and content.
are the product of white dwarf mergers is totally unknown. For instance, Dobbie et al. (2006) suggested that GD 50 (0346/C011) is associated with the star formation event that created the Pleiades, and this massive white dwarf is most likely a former member of this cluster. Hence the authors find no need to invoke a double white dwarf merger scenario to account for its existence. Thus, massive circumstellar disks may not be expected in all cases studied here.

6. CONCLUSION

In order to estimate the reliability of the 2MASS photometry for white dwarf stars, we defined a sample of 160 cool degenerates with $JHK$ magnitudes on the CIT photometric system taken from BRL97 and BLR01, and compared these values with those obtained from the 2MASS PSC. Our statistical analysis indicates that, on average, both data sets are consistent within the uncertainties, and thus that the 2MASS photometric data is appropriate for the study of white dwarf stars. The 2MASS data should still be interpreted with caution, however, especially for stars near the detection threshold, as significant discrepancies are to be expected.

We also concluded that the search for white dwarf and main-sequence star binaries based on 2MASS two-color diagrams is greatly limited by the 2MASS uncertainties when data below the level 1 requirements are considered. We demonstrated that some color regions identified by Wachter et al. (2003) and Wellhouse et al. (2005) to search for binary candidates are highly contaminated.
by single stars. We analyzed 47 binary candidates taken from the sample of Wachter et al. (2003) using the synthetic flux method and showed that this technique is a much more efficient tool for confirming binary candidates. We have also shown that the observed MIR photometry from the Spitzer Space Telescope agree very well with our model fluxes, a result that confirms the reliability of both the Spitzer photometry and our model atmosphere calculations up to 8 μm.

Finally, we searched for massive and large circumstellar disks, such as those predicted by Livio et al. (2005) around 57 massive white dwarfs (M > 0.8 M⊙). We showed that these systems would be clearly distinguishable from single stars in the 2MASS PSC, but such systems have not yet been identified in our analysis. Hence, high-mass circumstellar disks resulting from the merger of two white dwarfs must be uncommon around massive white dwarfs. We also showed that low-mass circumstellar disks such as those associated with G29-38, GD 362, and GD 56 are only barely identifiable except perhaps for the brightest level 1 white dwarfs in the 2MASS PSC.

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REFERENCES
Becklin, E. E., Farihi, J., Jura, M., Song, I., Weinberger, A. J., & Zuckerman, B. 2005, ApJ, 632, L119
Bergeron, P., & Leggett, S. K. 2002, ApJ, 580, 1070
Bergeron, P., Leggett, S. K., & Ruiz, M. T. 2001, ApJS, 133, 413 (BLR01)
Bergeron, P., Ruiz, M. T., & Leggett, S. K. 1997, ApJS, 108, 339 (BRL97)
Bergeron, P., Ruiz, M. T., Leggett, S. K., Saumon, D., & Wesemael, F. 1994, ApJ, 423, 456
Bergeron, P., Saffer, R. A., & Liebert, J. 1992, ApJ, 394, 228
Bessell, M. S. 1990, PASP, 102, 1181
Bessell, M. S., & Brett, J. M. 1988, PASP, 100, 1134
Borysow, A., Jorgensen, U. G., & Fu, Y. 2001, J. Quant. Spectrosc. Radiat. Transfer, 68, 235
Burleigh, M. R., Hogan, E., Dobbie, P. D., Napiwotzki, R., & Maxted, P. F. L. 2006, MNRAS, 373, L55
Carpenter, J. M. 2001, AJ, 121, 2851
Chary, R. R., Zuckerman, B., & Becklin, E. E. 1999, in The Universe as Seen by ISO, ed. P. Cox & M. F. Kessler (ESA SP-427; Noordwijk: ESA), 289
Cohen, M., Wheaton, W. A., & Megeath, S. T. 2003, AJ, 126, 1090
Debes, J. H., Sigurdsson, S., & Woodgate, B. E. 2005, AJ, 130, 1221
de la Fuente Marcos, R., & de la Fuente Marcos, C. 2005, NewA, 11, 59
Dobbie, P. D., Burleigh, M. R., Levan, A. J., Barstow, M. A., Napiwotzki, R., Holberg, J. B., Hubeny, L., & Howell, S. B. 2005, MNRAS, 357, 1649
Dobbie, P. D., Napiwotzki, R., Lodieu, N., Burleigh, M. R., Barstow, M. A., & Jameson, R. F. 2006, MNRAS, 373, L45
Ellis, G. L., Grayson, E. T., & Bond, H. E. 1984, PASP, 96, 283
Farhi, J., Becklin, E. E., & Zuckerman, B. 2005, ApJS, 161, 394
Farhi, J., Hoard, D. W., & Wachter, S. 2006, ApJ, 646, 480
Finley, D. S., Koester, D., & Basri, G. 1997, ApJ, 488, 375
Fulbright, M. S., & Liebert, J. 1993, ApJ, 410, 275
Gianninas, A., Bergeron, P., & Fontaine, G. 2006, AJ, 132, 831
Gianninas, A., Dufour, P., & Bergeron, P. 2004, ApJ, 617, L57
Green, P. J., Ali, B., & Napiwotzki, R. 2000, ApJ, 540, 992
Green, R. F., Schmidt, M., & Liebert, J. 1986, ApJ, 310, 205
Hansen, B. M. S., Kulkarni, S., & Wilkotowicz, S. 2006, AJ, 131, 1106
Holberg, J. B., & Bergeron, P. 2006, AJ, 132, 1221
Holberg, J. B., & Magargal, K. 2005, in ASP Conf. Ser. 334, 14th European Workshop on White Dwarfs, ed. D. Koester & S. Mochier (San Francisco: ASP), 419
Jura, M. 2003, ApJ, 584, L91
Kilic, M., von Hippel, T., Leggett, S. K., & Winget, D. E. 2005, ApJ, 632, L115
Kilic, M., von Hippel, T., Mullally, F., Reach, W. T., Kuchner, M. J., Winget, D. E., & Burrows, A. 2006b, ApJ, 642, 1051
Kowalski, P., & Saumon, D. 2006, ApJ, 651, L137
Lanning, H. H., & Pesch, P. 1981, ApJ, 244, 280
Leggett, S. K. 1992, ApJS, 82, 351
Leggett, S. K., Allard, F., Berriman, G., Dahn, C. C., & Hauschildt, P. H. 1996, ApJS, 104, 117
Leggett, S. K., Ruiz, M. T., & Bergeron, P. 1998, ApJ, 497, 294
Liebert, J., Bergeron, P., & Holberg, J. B. 2005, ApJS, 156, 47
Liebert, J., Green, R., Bond, H. E., Holberg, J. B., Wesemael, F., Fleming, T. A., & Kidder, K. 1989, ApJ, 346, 251
Livio, M., Pringle, J. E., & Wood, K. 2005, ApJ, 632, L37
Maxted, P. F. L., Napiwotzki, R., Dobbie, P. D., & Burleigh, M. R. 2006, Nature, 442, 543
McCook, G. P., & Sion, E. M. 1999, ApJS, 121, 1
Reach, W. T., Kuchner, M. J., von Hippel, T., Burrows, A., Mullally, F., Kilic, M., & Winget, D. E. 2005, ApJ, 635, L161
Schmidt, G. D., Liebert, J., Harris, H. C., Dahn, C. C., & Leggett, S. K. 1999, ApJ, 512, 916
Silvestri, N. M., Oswalt, T. D., & Hawley, S. L. 2002, AJ, 124, 1118
Wachter, S., Hoard, D. W., Hansen, K. H., Wilcox, R. E., Taylor, H. M., & Finkelstein, S. L. 2003, ApJ, 586, 1356
Wellhouse, J. W., Hoard, D. W., Howell, S. B., Wachter, S., & Esin, A. A. 2005, PASP, 117, 1378
Wesemael, F., Greenstein, J. L., Liebert, J., Lamontagne, R., Fontaine, G., Bergeron, P., & Glaspey, J. W. 1993, PASP, 105, 761
Wood, M. A. 1995, in White Dwarfs: Proc. 9th European Workshop on White Dwarfs, ed. D. Koester & K. Werner (Berlin: Springer), 41
Zuckerman, B., & Becklin, E. E. 1992, ApJ, 386, 260
———. 1987, Nature, 330, 138