Near-Infrared Photometric Analyses of White Dwarf Stars

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Abstract. We review the available near- and mid- infrared photometry data sets for white dwarfs from the Two Micron All-Sky Survey (2MASS) Point Source Catalog and the Spitzer Space Telescope. These data sets have been widely used to search for white dwarfs with an infrared excess as well as to characterize the atmosphere of cool white dwarfs. We evaluate the reliability of the 2MASS photometry by performing a statistical comparison with published JHK CIT magnitudes, and by carrying out a detailed model atmosphere analysis of the available photometry. We then present a critical examination of various results published in the literature including data from the Spitzer Space Telescope.

1. Introduction

With the recent All-Sky Data Release of the Two Micron All-Sky Survey (2MASS), we are now able to retrieve near-infrared (NIR) $J$, $H$, and $K_S$ 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 or circumstellar disks (Kilic et al. 2006a) and seeking binary candidates (Wachter et al. 2003). In addition to the 2MASS NIR photometry, there is a developing interest to observe white dwarfs at longer wavelengths in the mid-infrared (MIR). The Spitzer Space Telescope IRAC photometry has 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 (Hansen et al. 2006). 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.

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) and Bergeron et al. (2001, hereafter BLR01) who obtained improved atmospheric parameters of cool white dwarfs from a comparison of

\[ \text{See } \text{http://www.ipac.caltech.edu/2mass/releases/allsky/} \]

\[ \text{See } \text{http://ssc.spitzer.caltech.edu/irac/} \]
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. We searched the 2MASS PSC for all white dwarfs and we recovered the 2MASS $J$, $H$, and $K_S$ magnitudes for 160 stars from our initial CIT photometric sample of 183 objects.

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 in our sample. Note that the number of stars in each panel is different since some stars have not been formally detected in one or more bands in 2MASS. The size of the error bars in Figure 1 correspond to the combined quadratic uncertainties of both data sets, $\sigma = (\sigma_{2\text{MASS}}^2 + \sigma_{\text{CIT}}^2)^{1/2}$. 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.

Figure 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. 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 $K_S < 14.3$. 

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We present in Table 1 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. 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. We note that the offsets are typically five times smaller than the average 2MASS uncertainties (fifth column of Table 1) and these could as well be considered as zero for most practical purposes.

If the uncertainties of both data sets have been properly evaluated, the average combined quadratic uncertainties, $\langle \sigma \rangle$ (last column of Table 1), should be at least as large as the standard deviations of the magnitude differences. 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 $\langle \sigma \rangle$ 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.

Table 1. Statistical Comparison of CIT and 2MASS Magnitudes

| Bandpass \((m_{\text{CIT}} - m_{\text{2MASS}})\) | No. of Stars | Mean \((m_{\text{CIT}} - m_{\text{2MASS}})\) | Standard Deviation | $\langle \sigma_{\text{2MASS}} \rangle$ | $\langle \sigma \rangle$ |
|---|---|---|---|---|---|
| \(J\) | 159 | $-0.0046$ | 0.0805 | 0.0502 | 0.0745 |
| \(H\) | 157 | $+0.0180$ | 0.1126 | 0.0807 | 0.0997 |
| \(K/K_S\) | 143 | $+0.0247$ | 0.1561 | 0.1096 | 0.1253 |
| \(J\) \((S/N > 10)\) | 130 | $-0.0083$ | 0.0679 | 0.0409 | 0.0662 |
| \(H\) \((S/N > 10)\) | 97 | $+0.0094$ | 0.0675 | 0.0502 | 0.0726 |
| \(K/K_S\) \((S/N > 10)\) | 49 | $+0.0133$ | 0.0692 | 0.0466 | 0.0697 |

3. White Dwarfs and Low Mass Main Sequence Binaries from 2MASS

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.

In Figure 2, we compare 2MASS and CIT two-color diagrams for the 143 stars in our presumably single white dwarf sample of § 2 that have been detected by 2MASS in all three bandpasses. Using the color criteria of Wachter et al., illustrated in the left panel of Figure 2, we find that several binary and tentative binary candidates in both regions defined by Wachter et al. 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. The large amount of contamination of the binary candidate regions suggests that their criteria are not stringent enough.

Figure 2. Left: $(J - H)$ vs. $(H - K/K_{S})$ two-color diagrams for 143 cool white dwarfs taken from our sample and detected by 2MASS in all three bands. The filled and open points correspond to the CIT and 2MASS data, respectively. 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. Right: Same as the right panel but with the four regions defined by Wellhouse et al. (2005, see text)

Wellhouse et al. (2005) used a similar two-color diagram approach with a sample of 51 magnetic white dwarfs as candidates for potential pre-cataclysmic variables. They proposed to split the $(J - H, H - K_{S})$ two-color diagram into four regions, all illustrated on the right panel of Figure 2. While they did not find any binary candidates (II), they identified 10 objects with peculiar colors associated with very low mass companions or debris (regions III and IV). This represents a total of 28.6% of their sample with formal uncertainties with a possible companion or a disk. From our Figure 2, we find that 21% of the white dwarfs from our 2MASS sample of §2 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.

4. Spitzer Photometry

To evaluate the reliability of the Spitzer photometry, we use the observations of Kilic et al. (2006a) who have compared the Spitzer 4.5 and 8 $\mu$m photometric
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They found that the four hydrogen atmosphere white dwarfs with \( T_{\text{eff}} \) lower than 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.

We selected 12 white dwarfs with \textit{Spitzer} MIR flux from Kilic et al. (2006a) which are also in our cool white dwarf sample\(^3\) of § 2. We determine the atmospheric parameters for each star by fitting simultaneously the average fluxes for the nine photometric bands (\textit{BVRI}, \textit{JHK/CIT}, and \textit{Spitzer} 4.5 and 8 \( \mu \)m). 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. Furthermore, instead of assuming \( \log g = 8.0 \) for all objects, we constrain the \( \log g \) value from the trigonometric parallax measurements. The synthetic fluxes in the MIR are obtained by integrating our model grid over the \textit{Spitzer} IRAC spectral response curves while the observed fluxes are taken directly from Table 1 of Kilic et al. (2006b). 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 collision-induced opacity calculations and the Hummer-Mihalas occupation probability formalism for all species in the plasma.

We plot in Figure 3 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 agreement between the observed \textit{Spitzer} and model fluxes is very good at all temperatures. In particular, we do not observe any significant flux deficit at low effective temperatures as suggested by Kilic et al. (2006b). Therefore, we argue that the results presented in this section demonstrate the reliability of both the \textit{Spitzer} IRAC photometry and our model atmosphere grid up to 8 \( \mu \)m for studying cool white dwarfs.

5. Conclusions

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, 2MASS uncertainties are reliable but significant discrepancies are to be expected, especially for stars near the lower detection threshold. 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. We have also shown that the observed MIR photometry from the \textit{Spitzer Space Telescope} agree very well with our model fluxes.

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\(^3\)We left out LHS 1126 which indeed exhibits a Spitzer deficit. This peculiar so-called C\(_2\)H star also show NIR absorption explained by collision-induced opacity. This discrepancy may indicate that the collision-induced opacity calculations need to be improved at the high densities encountered in cool white dwarf atmospheres.
Figure 3. The ratio of observed to predicted Spitzer fluxes for 12 objects from the sample of Kilic et al. (2006b) as a function of effective temperature. For Ross 627 (1121+216), only the Spitzer 4.5 µm flux is used since the 8 µm flux is affected by a nearby star.

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