Cool companions to white dwarf stars from the Two Micron All Sky Survey All Sky Data Release

D. W. Hoard, S. Wachter

Spitzer Science Center, California Institute of Technology, MS 220-6, 1200 E. California Blvd., Pasadena, CA 91125

`hoard, wachter@ipac.caltech.edu`

and

Laura K. Sturch[1], Allison M. Widhalm[2,3], Kevin P. Weiler[4,5], Magaretha L. Pretorius[6], Joseph W. Wellhouse[1,3], Maxsim Gibiansky[1]

Spitzer Science Center, California Institute of Technology, MS 220-6, 1200 E. California Blvd., Pasadena, CA 91125

ABSTRACT

We present the culmination of our near-infrared survey of the optically spectroscopically identified white dwarf stars from the McCook & Sion catalog, conducted using photometric data from the Two Micron All Sky Survey final All Sky Data Release. The color-selection technique, which identifies candidate binaries containing a white dwarf and a low mass stellar (or sub-stellar) companion via their distinctive locus in the near-infrared color-color diagram, is demonstrated to be simple to apply and to yield candidates with a high rate of subsequent

[1]Department of Physics, Harvey Mudd College, 301 Platt Blvd., Claremont, CA 91711-5990

[2]Department of Physics and Astronomy, University of Southern California, Los Angeles, CA 90089

[3]Department of Astronomy, New Mexico State University, P.O. Box 30001, MSC 4500, Las Cruces NM 88003-8001

[4]Department of Physics, Marquette University, P.O. Box 1881, Milwaukee, WI 53201

[5]Department of Physics, DePaul University, Byrne Hall 211, 2219 N. Kenmore, Chicago IL 60614

[6]School of Physics & Astronomy, University of Southampton, Southampton, SO17 1BJ, United Kingdom

confirmation. We recover 105 confirmed binaries, and identify 28 firm candidates (20 of which are new to this work) and 21 tentative candidates (17 of which are new to this work) from the 2MASS data. Only a small number of candidates from our survey have likely companion spectral types later than M5, none of which is an obvious L type (i.e., potential brown dwarf) companion. Only one previously known WD + brown dwarf binary is detected. This result is discussed in the context of the 2MASS detection limits, as well as other recent observational surveys that suggest a very low rate of formation (or survival) for binary stars with extreme mass ratios.

Subject headings: binaries: general — infrared: stars — stars: low-mass, brown dwarfs — white dwarfs — stars: individual(WD0014+097, WD0017+061, WD0018-267, WD0023+388, WD0027-549, WD0034-211, WD0041+092, WD0104-331, WD0116-231, WD0130-196, WD0131-163, WD0145-705, WD0145-221, WDJ0148-255, WD0205+133, WD0208-153, WD0232+035, WD0237+115, WD0248+601, WDJ0254-053, WD0255+009.2, WD0257+247, WD0258+184, WD0303-007, WD0302+621, WD0308+096, WD0309-275, WD0312+019, WD0347-137, WDJ0357+286, WD0354+463, WD0357-233, WD0357+081, WD0413-077, WD0416+272, WD0419-487, WD0429+176, WD0430+136, WD0458-662, WD0627+299, WD0628-020, WD0710+741, WD0718-316, WD0752-146, WD0800-533, WD0802+387, WD0805+654, WD0812+478, WD0824+288, WD0852+630, WD0858-220, WD0908+226, WD0915+201, WD0928+399, WD0933+025, WD0937-095, WD0949+451, WD0950+185, WD0956+045, WD1001+203, WD1004-178, WD1013-050, WD1015-173, WD1026+002, WD1027-039, WD1033+464, WD1036-204, WD1037+512, WD1042-690, WD1049+103, WD1055-072, WD1101+364, WD1104+044, WD1106+316, WD1106-211, WD1123+189, WD1126+185, WD1132-298, WD1133+358, WD1136+667, WD1141+504, WD1147+371, WD1156+129, WD1201+437, WD1210+464, WD1213+528, WD1214+032, WD1218+497, WD1224+309, WD1246+299, WD1247-176, WDJ1255+258, WD1254-133, WD1305+018, WD1307-141, WD1310-305, WD1314+293, WD1319-288, WD1330+793, WD1333+487, WDJ1340+604, WD1401+005, WD1412-049, WD1412-109, WD1415+132, WD1424+503, WD1433+538, WD1435+370, WD1436-216, WD1443+336, WD1458+171, WD1501+300, WD1502+349, WD1504+546, WD1517+502, WD1522+508, WD1541-381, WD1558+616, WD1603+125, WD1608+118, WD1610+383, WD1619+525, WD1619+414, WD1622+323, WD1631+781, WD1632-227.1, WD1634-573, WD1643+143, WD1646+062, WD1654+160, WDJ1711+667, WD1717-345, WD1729+371, WDJ1820+580, WD1833+644, WD1845+019, WD1844-654, WD1950+279, WD2009+622, WDJ2013+400, WDJ2024+200, WD2101-364, WD2108-431, WD2118-333, WD2131+066, WD2133+463, WD 2151-015, WD2154+408, WD2237+819, WD2256+249, WD2311-068, WD2317+268, WD2318-

137, WD2326+049, WD2326-224, WD2336-187)

1. Introduction

White dwarf (WD) stars play key roles in a wide variety of astrophysically important scenarios. They represent not only the distant future of our own Sun, but are the endpoints in the evolution of the majority of stars in the Galaxy. As the relic cores of normal stars, WDs reveal the outcome of stellar evolution processes, and expose material created during a stellar lifetime of nuclear burning to direct examination. Yet, one of the most intriguing aspects of the observational study of WDs results simply from their role in facilitating the discovery of another type of object.

Detecting low mass stellar (or substellar) companions to WDs offers many advantages compared to main sequence primaries. In the latter case, faint low mass companions are often hidden in the glare of the more luminous main sequence primary, and radial velocity variations are small and, therefore, difficult to detect. Since WDs are typically $\sim 10^3$–10^4 times less luminous than main sequence stars, the brightness contrast compared to a potential faint companion is significantly reduced. Also, the markedly different spectral energy distributions of the WDs and their low mass companions makes the detection and separation of the two components relatively straightforward even with simple broad-band multi-color photometry. Observational searches for cool companions to WDs that take advantage of these factors have been carried out during the past several decades (e.g., Probst 1983; Zuckerman & Becklin 1987; Green et al. 2000).

In Wachter et al. (2003, henceforth, Paper I), we presented the Two Micron All Sky Survey (2MASS; Skrutskie et al. 2006) JHK_s photometry for all WDs from the McCook & Sion (1999, henceforth, MS99) catalog that were contained in the 2MASS Second Incremental Data Release (2IDR). We demonstrated that color-selection from the near-IR color-color diagram is an effective and efficient method for identifying candidate WD + low mass star binaries, via their near-IR excess compared to single WDs. In Paper I, we recovered all 48 of the known, unresolved WD + low mass star binaries in MS99 that were detected in the 2IDR sky coverage, and identified another 47 new candidate binaries. Our follow-up HST/ACS snapshot survey of candidates selected largely from Paper I has borne out the efficacy of this method, through the positive identification of a large fraction of resolved binaries with angular separations as small as $\sim 0.05''$ (see the first results from this survey in Farihi et al. 2006 – henceforth, Paper III – and discussion below).

In this work, we present the culmination of our correlation of the MS99 catalog with the

2MASS All Sky Data Release (ASDR). The results presented here are drawn from the final calibrated photometry for the objects from Paper I, as well as the remaining targets from MS99 that were not contained in the 2IDR sky coverage. Results for the subset of magnetic WDs were presented in Wellhouse et al. (2005, henceforth, Paper II), in which we did not find any strong binary candidates that could have been representative of the "missing" progenitor population of the magnetic cataclysmic variables (see discussion in Paper II and references therein). In Paper I and, especially, Paper II, we utilized 2MASS photometry with relatively large uncertainties, which could have lead to the inclusion of several single WDs in our lists of binary candidates. In this paper, we restrict our candidate sample to only those objects having 2MASS photometric uncertainties smaller than 0.1 mag in all three bands.

2. The Data

2.1. Target Selection and Identification

The source of our target sample is the MS99 catalog of optically spectroscopically identified WDs, which contains 2249 entries. Recently, a large number of new WDs have been discovered (e.g., from the Sloan Digital Sky Survey; Eisenstein et al. 2006). However, we restricted our potential targets to just the sample in MS99 since, as described in Paper II, the new WDs discovered by the SDSS are almost all too faint to have been detected by 2MASS. Our archival data were obtained from the 2MASS ASDR (Skrutskie et al. 2006), which includes JHK_s images and photometry covering 99.998% of the sky. The photometric signal-to-noise ratio is ≥ 10 for the objects in the 2MASS Point Source Catalog (PSC) with $J \leq 15.8$, $H \leq 15.1$, and $K_s \leq 14.3$. The overall detection limits of the survey are about 1 mag fainter in each band. The PSC contains astrometry and photometry for almost 471 million objects.

Because many WDs have large (and often unknown) proper motions, their astrometry sometimes becomes unreliable only a few years after their discovery. Consequently, to identify each WD in 2MASS, we first searched the literature for each object. In many cases we were able to locate published finding charts from the original, or a subsequent, identification of the WD; for example, from the LHS atlas (Luyten & Albers 1979), the Giclas proper motion survey and lists of suspected WDs (e.g., Giclas 1958 through Giclas et al. 1980), and the Montreal-Cambridge-Tololo survey (Lamontagne et al. 2000), to name only a few sources. These were compared with all available Digitized Sky Survey (POSS-I and POSS-II) and 2MASS images in order to identify the WD (after allowing for possible proper motion offsets, as described below).

In some cases, finding charts were not available in the literature. We then attempted to locate the WD using the most recent and accurate reported coordinates, proper motion, and/or blue optical color (e.g., by combining the POSS-II blue, red, and infrared images into a three-color composite)[1]. For example, when data from both surveys are available for a given WD, POSS-I and POSS-II provide images spanning decades, which makes proper motion based identification possible for high proper motion WDs. When POSS-I images were not available, POSS-II and 2MASS images were compared for small changes in apparent position. Some Luyten Half-Second Survey objects, reported in Bakos et al. (2002), fell into this category, and a combination of proper motion and precise coordinates was used for identification. Finally, we located the entry in the 2MASS PSC corresponding to the IR counterpart in the 2MASS images. Although this process is time-consuming, we estimate that simply using a coordinate match in the 2MASS PSC compared to MS99 would have resulted in up to 30–40% of the WDs being misidentified or erroneously reported as undetected.

The MS99 catalog contains 2249 objects. A number of the WDs have been subsequently reclassified as non-WDs (e.g., quasars) or non-existent (e.g., some WDs are listed twice in MS99 with different names, such as WD2009+397 = WDJ2013+400), leaving 2202 viable targets. Of these, we were unable to confidently recover the optical counterpart of the WD in 52 cases. For another 19 targets, even when we were able to recover the optical counterpart, the near-IR field proved to be too crowded to confidently identify the infrared counterpart. This leaves 2131 targets that we were able to confidently identify in optical and/or 2MASS images. Of these, 656 were not detected by 2MASS (i.e., not listed in the 2MASS All Sky PSC), leaving us with a final sample of 1475 WDs detected in the 2MASS ASDR.

2.2. Near-IR Photometry and Color-Color Diagram

As in Paper I, we graded the 2MASS photometry as "Good" (all 1σ photometric uncertainties ≤ 0.1 mag), "Moderate" (photometric uncertainty > 0.1 mag in one or more of the three bands), and "Poor" (no formal photometric uncertainty in one or more bands, signifying a low signal-to-noise value more properly treated as an upper limit). There are

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[1]We also checked all of our targets against the finding charts in the University of Arizona White Dwarf Database, at http://procyon.lpl.arizona.edu/WD/. However, this resource is still a work in progress and somewhat incomplete, and we found a number of instances in which the wrong star was identified as the WD (for example, often in the case of a wide common proper motion pair, the non-WD component was identified as the WD). Thus, whenever possible, we preferred to use this resource only to confirm our independent WD identifications rather than using it as a primary source.

417 Good detections, 475 Moderate detections, and 583 Poor detections. Figure 1 shows the near-IR color-color diagram constructed from our data, including the 1σ error bars of the Good data. The Moderate data are also shown (as unfilled grey points), but the Poor data are not plotted. Figure 2 is the same as Figure 1, except that, for clarity, we have not plotted the error bars on the Good data. We restrict the remainder of our analysis and discussion to the Good data.

The color-color diagrams are similar in appearance to those presented in Papers I and II. The primary difference compared to the color-color diagram in Paper I is the presence of a more populated and well-delineated "bridge" that extends almost vertically in the color-color diagram connecting the end of the WDs with colors similar to late main sequence stars to the bluer (and presumably single) WDs. This feature can be understood in the context of the color-color diagram for simulated WD + low mass star binaries shown in Figure 2 of Paper I, if one imagines how that figure would appear if the simulated binaries with $(H - K_s) > +0.4$ were removed. Thus, the bridge noted here is possibly identified as the tail end of the color distribution of candidate binaries containing WDs and the very lowest mass companions. The tentative candidates from Paper I were drawn from this region of the color-color diagram, and (as will be discussed below) probably were contaminated by single WDs with red colors and/or larger photometric uncertainties.

2.3. Binary Candidates

The color selection boundaries used here are shown as dotted lines in the figures. They correspond to $(J - H) \geq +0.396$ (equivalent to a dK0 star) and $(H - K_s) \geq +0.192$. All WDs outside (i.e., redward) of these boundaries were considered as candidate binaries. The reason for choosing the $(J - H)$ boundary is discussed in Paper I; however, the choice of the $(H - K_s)$ boundary is somewhat more arbitrary, and was guided primarily by our estimate of the middle of the "grey zone" between the single WDs and the end of the simulated binary color distribution shown in Paper I (coincidentally, this value corresponds to the $H - K_s$ color of a dM0 star). Table 1 lists the 2MASS All Sky PSC photometry for all of the 154 WDs with near-IR excess selected in this fashion.

After compiling our list of WDs with near-IR excess, we re-examined the available literature for each of them in order to determine which ones are known binaries. We then sorted each WD into one of three categories: confirmed, candidate, and tentative. Confirmed binaries are those targets whose binary nature has been conclusively established in the literature, typically via spectroscopic detection of an unresolved low mass star, resolved imaging of the binary components, and/or detailed photometric modeling showing the presence of

a low mass star spectral energy distribution after the WD is removed. Candidate binaries are those targets with near-IR excess reported, but not yet thoroughly investigated, in this work, Paper I, and/or other literature sources. Tentative candidates are those targets for which there is substantial reason to doubt that the observed near-IR colors actually indicate the presence of a cool, low mass binary companion; for example, targets that fall into this category include DC (carbon) type WDs, possible WD+WD binaries, WDs with less certain optical identifications, etc. In addition, any target selected as a candidate solely because it satisfies the $(H - K_{\mathrm{s}})$ criterion (but not the $J - H$ criterion) was categorized as tentative if its $(H - K_{\mathrm{s}})$ color was within 1σ of the $(H - K_{\mathrm{s}})$ color selection limit. Not surprisingly, slightly more than half (12 out of 21) of the tentative candidates are drawn from the subset of WDs selected only because they satisfy the $(H - K_{\mathrm{s}})$ criterion.

Table 2 lists the binary status of each of the WDs from Table 1, along with some supplemental information. The columns of Table 2 are as follows: (1) WD name, as listed in Table 1; (2) binary status, as described above; (3) literature sources used to establish the binary status ("this work" is not listed unless it is the only source or contains crucial evidence supporting the binary status – see column 8); (4) and (5) estimates of the spectral types and angular separation of the binary components, if applicable (the 2MASS colors reported here are used to estimate a spectral type when possible; however, this estimate does not account for the presence of the WD, so the true spectral type is likely to be later than the nominal estimate); (6) the type of data used to establish the information in columns (4) and (5) (I = imaging, P = photomery, S = spectroscopy); (7) literature source(s) for the information in columns (4)–(6); (8) key for the presence of additional comments about individual WDs, listed in Appendix A. Multiple rows of data in columns (4)–(7) are sometimes available for a given WD.

2.3.1. Anomalous Objects

Two objects stand out in the color-color diagram and deserve further explanation here (also see the corresponding notes in Appendix A). WD1201+437 is the object located at extremely red $(H - K_{\mathrm{s}})$ color and is possibly a quasar. WD1517+502 is the only object located in the L spectral type region of the color-color diagram, but it is a known binary in which the WD's companion is a dwarf carbon star, not an L dwarf.

WD2326+049 formally qualifies for inclusion in our list of color-selected binary candidates, but has been excluded from the tables in this work because it is known to be surrounded by a dust disk (e.g., Graham et al. 1990, Tokunaga et al. 1990, Jura 2003, Reach et al. 2005), and the presence of binary companions has been excluded down to angu-

lar separations of $a \geq 0.9''$ and masses of $M_2 \geq 6M_{\mathrm{J}}$ (Debes et al. 2005a). For comparison with our known and candidate binaries, we have plotted the 2MASS colors of WD2326+049 and the other known WD with a dust disk (WD1729+371 = GD 362; Becklin et al. 2005) with special symbols in the figures. The near-IR colors of these two WDs with dust disks are similar to each other. They satisfy only the $(H - K_{\mathrm{s}})$ color selection criterion, but fall outside the expected locus for WD + very low mass companion binaries shown in the simulation from Paper I. There are several WDs whose 1σ uncertainty ranges overlap with the WD + dust disk colors, but none whose nominal colors match.

2.4. Number Statistics

Table 3 lists the total number of WDs with near-IR excess reported in this work, as well as the break-down into each of the three binary status categories used in Table 2 (i.e., confirmed, candidate, tentative). We also show the numbers of WDs that are newly reported in this work and the current status of the binary candidates/WDs with near-IR excess reported in Paper I. Of the 154 objects reported in this work, 54% are new, and the remainder were first reported in Paper I. At the time of Paper I, only about one-half of our reported WDs with near-IR excess were already known to be binaries, but in the intervening years, more work has been accomplished in this field, and the fraction of confirmed binaries (as reported in the literature) from our total sample in this work is close to 70%. For example, 20 of the candidates from Paper I were subsequently confirmed by us to be binaries at small angular separations that are resolvable by HST+ACS (Paper III). This leaves 28 firm binary candidates (20 of which are new to this work) and 21 tentative candidates (17 of which are new to this work).

Of the 95 candidates from Paper I, 27 are "missing" from our current sample of WDs with near-IR excess. Fifteen of these were removed because of better identification information[2] that leaves them as either undetected by 2MASS or with their identifications uncertain. Another nine were excluded from the current candidate list because they have only Moderate or Poor 2MASS detections. The remaining three "missing" WDs are equally divided among being reclassified as something other than a WD, not satisfying the red selection criteria with the recalibrated All Sky photometry, and not being included in the All Sky PSC. Of the 15 tentative candidates from Paper I, all but three have been excluded from the current candidate list because they have only Moderate 2MASS detections.

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[2]A few of these were noted independently in Tremblay & Bergeron (2007).

3. Analysis and Discussion

3.1. Discussion of the Synthetic Photometry Method

Tremblay & Bergeron (2007) have recently suggested that a method involving calculation of synthetic photometry from WD model atmospheres is more efficient than our color-selection technique as a means to identify WDs with near-IR excess that are binary candidates. While the former method is undeniably effective and possibly has a lower "false positive" rate, it requires multi-band optical and near-IR photometry for each target, and is also more computationally and analytically complex than simple color selection from the pre-existing, homogenous 2MASS PSC. Consequently, we suggest that the latter method is, in fact, the more *efficient* method of identifying binary *candidates*, in terms of simplicity and ease of use (also see §3.2.1). The synthetic photometry method is likely more effective at providing subsequent confirmation and characterization of the near-IR excess in color-selected binary candidates (e.g., see discussion of WD0145-221 in §3.2.2).

3.2. Comparison with the Paper I Results

3.2.1. Current Status of Past Binary Candidates

Overall, our "success" rate in finding binary candidates using 2MASS color selection that were subsequently confirmed as binaries is very high. For example, in Paper I, we reported 47 new binary candidates (excluding the tentative candidates). Eighteen of these have now been excluded from our sample for reasons other than simply having Moderate or Poor 2MASS detections (see §2.4). Of the remaining 29, 28 have been confirmed as binaries by us in Paper III via high angular resolution imaging (20 objects) or using a method similar to that described by Tremblay & Bergeron (2007) (8 objects). So, our confirmed success rate is 80% (including the 48 already known binaries recovered as part of the original 95 candidates in Paper I), while our confirmed false positive rate (for targets that have been rejected as misidentifications in Paper I) is only 19% (the remaining 1%, one WD, is, as yet, neither confirmed as a binary nor rejected from the sample). In this work, 68% of the reported WDs with near-IR excess are recovered from already known or recently confirmed binaries. We conclude that the near-IR color selection method is not only simple to apply, but also has a high success rate and correspondingly low rate of false positives (most of which are attributable to incorrect target identifications, not erroneous color-selection of single WDs).

Of the 15 tentative candidates reported in Paper I, only 3 remain in the sample reported in this work (with the rest having been excluded for having large uncertainties on their

2MASS photometry). One of these three has been confirmed as a binary, one has been "upgraded" to a firm candidate due to a decrease in the uncertainties of its recalibrated photometry in the All Sky PSC, and the third remains a tentative candidate. Eight of the 12 excluded targets are now believed to be single WDs (e.g., as described in Paper II and Tremblay & Bergeron 2007). There is a total of 21 tentative candidates reported in this work, 12 of which were selected because they satisfy only the $(H - K_{\mathrm{s}})$ criterion (i.e., they are the targets identified with the simulated binaries containing the lowest mass companion stars). However, three of the targets selected from only the $(H - K_{\mathrm{s}})$ criterion are confirmed binaries (with the remainder of the $H - K_{\mathrm{s}}$-selected objects in the candidate class). So, in this regard, we note that it is important when utilizing *any* method of selecting binary candidates to heed the warning implied by the label *tentative* candidate, but that rejecting these systems outright would result in the loss of a not insignificant fraction of true binaries[3].

3.2.2. Where Are the Binaries Containing Brown Dwarfs?

Since the near-IR color-color diagram shown in Figures 1 and 2 contains over 60% more red-excess WDs than the color-color diagram from Paper I, a pertinent question is: why doesn't the current color-color diagram look more like the simulated diagram from Paper I? Put another way, where are the binaries containing a WD and M5+ or L type (potential brown dwarf) companion? Discounting WD1517+502 (see §2.3.1), there are *no* observed candidates in the L spectral type region of the color-color diagram. Only eight targets in total (again excluding the two objects with anomolous colors – see §2.3.1) have nominal colors redward of the $(H - K_{\mathrm{s}})$ color of a dM5 star, although several times this many have colors within 1σ of this boundary (see vertical dashed line in Figures 1 and 2). Of the confirmed binaries in our sample, only six have estimated spectral types for the companion later than M5 (WD0145-221, WD0354+463, WD0419-487, WD0710+741, WD0752-146, and WD2151-015 – see Table 2 and Figure 2). Of these, only WD0145-221 has an L type companion (L6–7; i.e., a "true" brown dwarf); the rest have companion spectral types of M6–8. However, the

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[3]Incidentally, WD0518+333, which was identified as a tentative binary candidate in Paper I and is reported by Tremblay & Bergeron (2007) as a single WD, is shown by our high angular resolution imaging to have a faint neighbor at a separation of $a \approx 1.9''$ in 2005 (from a paper currently in preparation). If the neighbor is associated with the WD, then this is slightly below the expected 2MASS imaging resolution limit. If the neighbor is not associated with the WD (hence, does not share its proper motion), then the separation would have been $a \lesssim 0.5''$ at the time of the 2MASS observation in 1998. Thus, this neighbor possibly contaminated the 2MASS photometry. We note that the known bright common proper motion companion to the WD (located $\approx 8''$ northeast) is also resolvable into a close ($a \approx 0.15''$) pair of stars that are approximately equally bright at I band.

near-IR colors of WD0145-221 are most similar to an early dK star – nowhere near the L spectral type region in the color-color diagram! This object is at a distance of $d \approx 39$ pc, so the companion star alone would not have been detected at the Good level by 2MASS (see below), and over 90% of its J-band flux is attributed to the WD (Farihi & Christopher 2004; Farihi et al. 2005b). Although there is an observed excess in both H and $K_{\rm s}$ bands compared to a single WD model, the observed slope of the spectral energy distribution from H to $K_{\rm s}$ mimics that of the WD component (see Figure 1 in Farihi et al. 2005b). When combined with the almost complete lack of a J-band excess, the true nature of this binary is obfuscated in the color-color diagram. Although color-selected as a binary candidate, the brown dwarf nature of the companion is revealed only through additional analysis. It is possible then, that some binaries with brown dwarf companions are similarly "hiding" in the near-IR color-color diagram among the total sample of red-excess WDs.

However, we should also explore this issue from the point-of-view of the assumptions that went into the simulation from Paper I, compared to the real characteristics of the 2MASS survey and the expectations for the presence of WD + brown dwarf binaries. In this context, part of the answer lies in the fact that the simulation in Paper I assumed that all of the simulated binaries are located at $d = 10$ pc and that all of them are detectable by 2MASS. In fact, most ($\sim 70\%$) of the WDs from Table 1 have distance estimates in the literature (e.g., compiled in Paper III; Holberg et al. 2002; Silvestri et al. 2002; Farihi et al. 2005a; Liebert et al. 2005), and we find an average distance of $d = 150$ pc for our binary candidates, with distances ranging from ≈ 5–700 pc (plus one 7σ outlier at $d = 1660$ pc). Table 4 lists the absolute magnitudes of late main sequence spectral types, along with the corresponding maximum distance moduli for detection within the $S/N \geq 10$ photometric limits of 2MASS (see §2.1). So, for example, stars later than M5–6 are only detected (at the Good level) if they are closer than $d \approx 150$ pc (distance modulus of 5.88), while stars later than L6 are only detected if they are closer than $d \approx 25$ pc (distance modulus of 1.99).

The table also lists the mean photometry for the sample of single WDs used in the simulation from Paper I. If we take these values as representative, then for a given WD + low mass star binary, the components will be approximately equally bright in the J and H bands for companion spectral types of L3–5 and L5–6, respectively. The WD never exceeds the $K_{\rm s}$-band brightness of the companion at even the latest L spectral type. In the case of binaries containing equally bright components (in a particular photometric band), the combined absolute magnitude is 0.75 mag brighter than either component alone, allowing for detection out to a factor of $\sqrt{2}$ larger distance. However, as the companion spectral type becomes earlier or later, the combined photometry of the binary is rapidly dominated by the companion or the WD, respectively, and the maximum distance modulus for a Good detection in 2MASS rapidly converges back to the single star values listed in Table 4. Thus,

we should expect that binaries containing late-M or mid-L companions should be detectable at the Good level in 2MASS out to distances of $d \approx 150$ pc or $d \approx (25)(\sqrt{2}) = 35$ pc, respectively. While this does imply that there will be fewer detected binaries containing mid-L companions than late-M companions, it does not imply the almost complete non-detection of the former that we observe.

To further test this theory, we modified the simulation from Paper I to randomly assign a distance from a distribution equivalent to that for our current targets, and then reject simulated binaries that would not be detected in 2MASS at the Good level. We also tried a number of different distance distributions, such as increasing the relative number of targets at a given distance, d, in proportion to d^2 between several minimum and maximum distances, or assuming a strongly peaked population at a specific distance that falls off for larger and smaller distances. As suspected, although in all cases introducing some kind of distance dependence on the dectability of a simulated binary results in fewer late spectral type binaries in the simulated color-color diagram, there are still a substantial number of "detected" binaries with late-M to mid-L companions, which are not present in large numbers in the observed color-color diagram.

We can also explore the effect of the observed relative numbers of stars as a function of spectral type (or mass). By default, the simulation from Paper I (which was constructed purely to illustrate the possible loci of near-IR color-color space occupied by WD binaries) considers a binary with an M type companion to be as likely as a binary with an L type companion. In reality, however, only about 35% of the field stars within 20 pc have spectral types of M5 or later and only about 5% have spectral types of L0 or later; most ($\approx 50\%$) have spectral types of M3–4 (e.g., as compiled in Farihi et al. 2005a; see their Figure 7). Taken at face value (however, see below), this suggests an explanation for why we *do* observe numerous candidate binaries with near-IR colors equivalent to main sequence stars up to spectral type of M4–5. Considering the distribution of field star spectral types, from our sample of 154 confirmed and candidate WD binaries, we might expect 50–55 to contain dM5+ type companions, ≈ 8 of which are L type companions. Approximately 50% of the red-excess WDs with known distances are closer than $d \approx 150$ pc (i.e., detectable if they contain a late-M companion); approximately 20% are closer than $d \approx 35$ pc (i.e., detectable if they contain a mid-L companion). So, to first order, we might still expect to detect 25–30 binaries with dM5+ companions, of which 1 or 2 have mid-L companions. The latter is roughly in agreement with our observed sample, if we count WD0145-221 as the one detected WD + brown dwarf binary; however, the former is consistent only if we count essentially all of the binary candidates within 1σ of the $(H - K_\mathrm{s})$ color of a dM5 star as binaries containing dM5+ companions.

Of course, the situation is more complex than this, since numerous recent surveys for WDs in binaries with low mass companions have noted that there appears to be a mechanism that makes the existence of binaries containing a WD and very low mass (late-M through L type) companion less likely than that of a WD + mid-M or earlier companion, in excess of the relative numbers of low mass field stars of these spectral types. The well-known "brown dwarf desert" describes an observed dearth of solar-type stars (i.e., WD progenitors) in binaries with brown dwarf companions at separations $r \lesssim 5$ AU, compared to the frequency of low mass star + brown dwarf and brown dwarf + brown dwarf binaries (e.g., Marcy & Butler 2000; Grether & Lineweaver 2006). The brown dwarf desert might extend out to at least many hundreds of AU, although there is some evidence that the desert does not extend past separations of $r \gtrsim 1000$ AU (Gizis et al. 2001; however, also see the apparently contradictory results from Farihi et al. 2005a – discussed below – and McCarthy & Zuckerman 2004). An additional factor that could contribute to a lack of WDs with (close) brown dwarf companions is the possible destruction or outspiraling of pre-existing low mass companions during the post-main sequence evolution of the WD progenitor (described in Paper III and references therein).

At distances of 5–400 pc, and assuming an angular resolution limit of $\sim 2''$, the binaries in our sample have likely separations of $r \lesssim 10$–800 AU. Farihi et al. (2005a) performed a search of 261 WDs sensitive to low mass companions at separations of $r \sim 100$–5000 AU and an additional search of 86 WDs sensitive to low mass companions at separations of $r \sim 50$–1100 AU. They detected *no* brown dwarf companions, implying that the fraction of WD + brown dwarf binaries, even at large separations, is $< 0.5\%$ and does not reflect the larger relative populations of field stars of M–L spectral types (also see, for example, Politano 2004 and Dobbie et al. 2005). The Farihi et al. (2005a) fraction corresponds to $\lesssim 1$ WD + brown dwarf binary expected in our sample of 154 red-excess WDs, which is, again, consistent with the presence of WD0145-221. Clearly, this result must be treated circumspectly because of the small number of expected, and observed, objects in this category, not to mention the fact that the likely range of sampled orbital separations is somewhat different between our survey and the Farihi surveys, which could produce an even smaller expected number of WD + brown dwarf binaries in our sample (because of the small numbers of red-excess WDs and very small expected fraction of WD + brown dwarf binaries, we did not attempt to quantify or correct for this effect). However, Farihi et al. (2005a, their Figure 6) show that M5–9 stars *as binary companions to WDs* are found in only about 10% of the observed systems, compared to a frequency of about 30% in the field (however, as with the distribution of field stars, the peak spectral type for companions again occurs at M3–4). Thus, we should only expect ≈ 15 WD binaries containing an M5–9 star, which is more consistent with the observed (small) number of candidates whose nominal $(H - K_s)$ color is redward of that of

a dM5 star.

4.   The Conclusions

We have identified a large sample of candidates for binaries containing a WD and a cool main sequence star of spectral type as late as approximately M4–5. However, we found only a small number of strong candidates for binaries containing companions of spectral types later than M5, and *no* new candidates for binaries containing an L type (i.e., potential brown dwarf) companion. This result is in agreement with the results from other recent searches for WD binaries, which suggest that the formation (and/or survival) rate for binaries with extreme mass ratios[4] is very low.

An important result of our near-IR survey of WDs, begun in Paper I and culminating here, is simply the demonstration that the color-selection method is a viable technique for selecting binary candidates and has a high confirmed success rate. The synthetic flux method (used in Paper III and Tremblay & Bergeron 2007) is a logical *next* step, since it requires both additional data (e.g., multiple optical and infrared bands) and the calculation of synthetic photometry from model atmospheres for each candidate star (e.g., it would have been impractical to attempt this type of analysis as a first step for the entire MS99 catalog). In the modern era of virtual observatories and all sky surveys (e.g., the upcoming all sky infrared surveys to be performed by the Wide-field Infrared Survey Explorer and Akari/ASTRO-F), the color-selection method that we have demonstrated using 2MASS photometry provides the most simple and efficient means to take advantage of existing, homogenous survey data in order to provide an initial list of binary candidates.

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[4]That is, $M_2/M_{\mathrm{pro}} \lesssim 0.05$, where M_2 is the initial mass of the companion and M_{pro} is the mass of the WD progenitor. The initial companion mass could be smaller than the current companion mass due to material accreted by the companion during the post-main sequence evolution of the WD progenitor (summarized in §5.4 of Farihi et al. 2005a). The progenitor mass, in turn, is likely a factor of $\gtrsim 2$ larger than the current WD mass (up to ~ 10 times larger for massive WDs; e.g., Weidemann 1987, 2000).

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A.   Notes on Individual Objects

WD0018-267: Included (but not discussed) in Kilic et al. (2006); does not show mid-IR excess compared to model WD in their Figure 1.

WD0023+388: Reference to binary status in MS99 is a private communication.

WD0034-211: MS99 note "close double degenerate binary" but Bragaglia et al. (1990) reclassified it as a WD+dM.

WD0041+092: BL Psc.

WD0116-231: Eggen & Bessell (1978) and Lamontagne et al. (2000) classify WD0116-231 as DA+dM (the latter may just be repeating the Eggen & Bessell classification); however, Bessell & Wickramasinghe (1979) list WD0116-231 in their table of composite spectrum stars (dK or dM plus a blue star) as type sd0. Reference for binary status in MS99 is a preprint indicating the Montreal-Cambridge survey, with no obvious subsequent publication.

WD0130-196: MS99 note "MCT0130-1937 is a PG 1159 star with no detected variability."

WDJ0148-255: WD0145-257.

WD0232+035: FS Cet, Feige 24. Orbital period of 4.232 d (Thorstensen et al. 1978; Ritter & Kolb 2003).

WDJ0254-053: WD0252-055, HD18131.

WD0255+009.2: The 2MASS colors do not strongly constrain a spectral type or luminosity class.

WD0257+247: Reference for binary status in MS99 is a private communication that probably refers to the wide ($a \sim 140''$) common proper motion companion (NLTT 9583) reported by Salim & Gould (2003).

WD0258+184: Possibly an sdB star, with an unresolved cool (G8) companion, misclassified as a WD in MS99 (Lisker et al. 2005).

WD0302+621: Schmidt & Smith (1995) find a marginal detection of an $\sim$kG magnetic field, but no sign of a red companion in its optical spectrum (they were not specifically looking for binaries, but noted the possible presence of a red spectral component in several other WDs in their survey).

WD0308+096: CC Cet. Orbital period of 0.287 d (Ritter & Kolb 2003).

WD0312+019: The 2MASS colors do not strongly constrain a spectral type.

WDJ0357+286: WD0353+284, V1092 Tau. Orbital period of 0.365 d (Jeffries et al. 1996). The WD may be accreting from the wind of its ultra-fast rotating companion (Jeffries et al. 1996; Jeffries & Smalley 1996).

WD0413-077: 40 Eri B. The BC pair (A is a distant dK1 star) should be resolvable in 2MASS images but the dM star is either undetected or unseen due to the brightness of the WD.

WD0416+272: HL Tau 76, V411 Tau. A ZZ Ceti variable (MS99). Not identified as a binary in Farihi et al. (2005a).

WD0419-487: RR Cae. Orbital period of 0.304 d (Ritter & Kolb 2003).

WD0429+176: HZ9. Orbital period of 0.564 d (Ritter & Kolb 2003).

WD0458-662: Likely orbital period of ~ 0.7 d to several days (Hutchings et al. 1995).

WD0627+299: Not identified as a binary in Farihi et al. (2005a).

WD0628-020: Angular separation is near the 2MASS imaging resolution limit; however, no separate 2MASS data are available for the WD component, so the photometry results might be for the companion only.

WD0710+741: HR Cam. Orbital period of 0.103 d (Ritter & Kolb 2003).

WD0718-316: IN CMa. Orbital period of 1.262 d (Ritter & Kolb 2003).

WD0800-533: Wickramasinghe & Bessell (1977) suggest that this object is a possible cataclysmic variable; they don't show its spectrum, but say that Hα and Hβ have emission line cores, and that it is a possible old nova. Red near-IR colors reported independently by Kawka et al. (2007).

WD0802+387: Hot DZ star with strong Ca II H and K absorption lines (Sion et al. 1990). Not identified as a binary in Farihi et al. (2005a).

WD0852+630: Reference for binary status in MS99 refers to wide ($a \approx 36''$) common proper motion companion.

WD0858-220: Reference for binary status in MS99 is a private communication. Barely resolved in 2MASS images; only one source in 2MASS PSC, at position between the two stars, so the photometry could be for only the dM star or a blend of both.

WD0908+226: Reference for binary status in MS99 is a private communication (no other literature citations).

WD0915+201: Stellar image is slightly elongated (diameter $\approx 3''$) in red POSS images, and shows a distinct color gradient from blue at the northernmost end to red at the southernmost end in the combined POSS B+R+IR 3-color image. The 2MASS source position is offset toward the red end and there is no corresponding 2MASS source at the blue end, so it is possible that the 2MASS photometry corresponds only to the red star (i.e., the WD is undetected) or is a blend of both stars. The 2MASS colors do not strongly constrain a spectral type.

WD0937-095: Reference for binary status in MS99 is a private communication, and probably refers to the $a \approx 13''$ common proper motion companion. There is some ambiguity in the literature about which star in the pair is the WD: 2MASS 09394969$-$0945562 is a closer match to the catalog coordinates of the WD (Salim & Gould 2003) than the southern component (2MASS 09394977$-$0946098); however, both stars are about equally red in th near-IR (e.g., $J - K_{\rm s} \approx$ 0.80–0.81). We have used the northern component here, but the 2MASS photometry for the southern component was reported in Paper I.

WD0949+451: The red star is possibly a dM4.5+dM4.5 close binary separated by $0.009''$ (Paper III). Reference for binary status in MS99 is a preprint citing the Hamburg-Schmidt Catalog with no published follow-up.

WD1013-050: Orbital period of 0.789 d (Ritter & Kolb 2003).

WD1026+002: UZ Sex. Orbital period of 0.597 d (Ritter & Kolb 2003).

WD1027-039: Reference for binary status in MS99 is a private communication, and probably refers to the wide ($a \approx 35''$) common proper motion companion reported by Salim & Gould (2003).

WD1036-204: MS99 note "a polarized, carbon band, magnetic degenerate"; this might account for its near-IR colors instead of a red companion (see Paper II).

WD1042-690: Orbital period of 0.337 d (Ritter & Kolb 2003).

WD1055-072: An unusual DC type WD (Bergeron et al. 2001). No evidence for an unresolved red companion in the surveys of Debes et al. (2005b); Farihi et al. (2005a); Kilic et al. (2006). Included (but not discussed) in Kilic et al. (2006); does not show mid-IR excess compared to model WD in their Figure 1.

WD1101+364: MS99 note "double degenerate DA+DA double-lined" (also see Marsh 1995; Nelemans et al. 2005). Orbital period of 0.145 d (Ritter & Kolb 2003).

WD1104+044: Inspection of the POSS and 2MASS images shows that this is a not quite resolved ($a \approx 3''$) common proper motion binary containing a very blue object (presumably the WD) and a red object; only the red object is detected by 2MASS.

WD1106-211: Although it is the closest star to the correct coordinates, it is possible that this is not the WD because it does not display the large proper motion ($\mu = 0.467''$ y^{-1}) reported by Evans (1992) (however, no star within several arcminutes shows such proper motion).

WD1126+185: Possibly an sdB+dG–K binary (Farihi et al. 2005a).

WD1132-298: ESO0439-095. This spectroscopic binary has a pair of wide ($a \approx 53''$) common proper motion companions (ESO0439-096A+B, which form an $a \approx 4''$ binary themselves) that are dM2 and dM3 stars, respectively.

WD1136+667: Orbital period of 0.836 d (Ritter & Kolb 2003).

WD1156+129: This object has the correct optical brightness ($V \sim 17.5$), position, and proper motion ($\mu = 0.05''$ y^{-1} at position angle of $\theta = 176°$; Evans 1992), but is very red ($V - J \approx +2.8$).

WD1201+437: Xu et al. (1999) classify this object as a quasar; however, their X-ray position error circle has a $9''$ radius. The extremely red 2MASS colors of this object (e.g., $H - K_{\mathrm{s}} \approx +1.1$) lend credence to reclassifying it as a quasar.

WD1213+528: EG UMa. Orbital period of 0.668 d (Ritter & Kolb 2003).

WD1224+309: LM Com. Orbital period of 0.259 d (Ritter & Kolb 2003).

WD1247-176: Orbital period of 0.571 d (Ritter & Kolb 2003).

WDJ1255+258: WD1253+261, IN Com. Planetary nebula central star (PN G339.9+88.4). The hot ($T > 100,000$ K; Feibelman & Kaler 1983) component in IN Com is widely referred to as a subdwarf or WD precursor (e.g., Ritter 1986). It has been suggested in several literature sources that IN Com might be a triple system containing a close (possibly interacting) binary and a detached third component (likely a late M dwarf), although the identification of which stars are involved in the close vs. wide binaries, and their corresponding orbital periods, has not been conclusively established (summarized in Strassmeier et al. 1997).

WD1305+018: Stellar image is slightly elongated (diameter $\lesssim 2''$) in the east-west direction in the POSS and 2MASS images; the west end is slightly bluer than the east end, but there is no strong color gradient. Optical colors are redder than expected from its spectroscopic temperature, indicating a possible cool companion (Cheselka et al. 1993).

WD1310-305: Not a close double WD binary (Maxted & Marsh 1999).

WD1314+293: HZ43. Reference for binary status in MS99 is a private communication.

WD1330+793: Reference for binary status in MS99 is a private communication. Only the red, eastern component of this common proper motion binary is detected by 2MASS.

WDJ1340+604: WD1339+606.

WD1412-109: Stellar image appears slightly elongated in POSS and 2MASS images; there is a slight color gradient in the combined POSS B+R+IR 3-color image, with northwest end (faintly) red.

WD1424+503: There is a red (dMe) star $\approx 7.5''$ north of the WD (e.g., Mason et al. 1995) that is easily resolved in the POSS and 2MASS images (and the 2MASS PSC); it is not known if this star is gravitationally bound with the WD. In addition, there is previous evidence for the WD having a close (unresolved) red companion (summarized in Schwartz et al. 1995).

WD1433+538: Possibly a double degenerate (Liebert et al. 2005).

WD1443+336: Possible cataclysmic variable (Green et al. 1986).

WD1501+300: This is the object closest to the (imprecise) target coordinates listed in MS99, and is identified in the University of Arizona White Dwarf Database finding chart. However, there is a faint, blue star $\approx 72''$ west that might be the actual WD.

WD1517+502: The companion in this binary is a dwarf carbon star; its 2MASS colors mimic very late M to early L spectral type.

WD1541-381: Reference for binary status in MS99 is a private communication, probably refers to the wide $(10.3'')$ common proper motion companion reported by Luyten (1949). This object is also reported as DA+dM (Bessell & Wickramasinghe 1979), but this might also refer to the wide companion. The wide companion (2MASS 15451177−3818493) is slightly elongated in the northwest-southeast direction in the POSS (red) and 2MASS images and may, itself, be a close binary. The 2MASS photometry for both stars (the alleged WD and the wide companion) is equally red: $(J - H) = +0.52$ and $(H - K_\mathrm{s}) = +0.24$–0.32.

WD1558+616: Reference for binary status in MS99 is a preprint citing the Hamburg-Schmidt Catalog with no published follow-up.

WD1603+125: The WD has an 8 MG magnetic field (Wegner & Swanson 1990a).

WD1608+118: Stellar image is slightly elongated in the POSS images, with a strong color gradient in the combined POSS B+R+IR 3-color image from red at the northwest end to blue at the southeast end. The 2MASS detection is offset toward the red end.

WD1610+383: Inspection of POSS and 2MASS images shows that this is a common proper motion binary, barely resolved in the POSS images as a blue (southwest) and red (northeast) pair. The single 2MASS detection is located closer to the red star – see note in Paper I. There is also a much fainter star of intermediate (optical) color just north of the red component, but it does not appear to share proper motion with the binary.

WD1619+525: Stellar image is slightly elongated in east-west direction in (red) POSS images, with a color gradient in the combined POSS B+R+IR 3-color image from blue (east) to red (west).

WD1622+323: Finley et al. (1997) report an early M type companion from an optical spectrum of this object.

WD1631+781: Orbital period of 2.89 d (Ritter & Kolb 2003).

WD1632-227.1: Double degenerate (DC+DC) binary with separation of $a = 5.75''$, resolved in all POSS and 2MASS images; component 1 is the northern, and somewhat brighter, of the two. We note that component 2 is even more red in the near-IR ($J - H \approx +0.7$, $H - K_\mathrm{s} \approx +0.5$), but is not included here because it is a Moderate 2MASS All Sky detection ($\sigma_{K_\mathrm{s}} > 0.1$ mag). The 2MASS colors do not strongly constrain a spectral type.

WD1634-573: MS99 note "Hot (55,000 K) DO degenerate with photospheric carbon in UV."

WD1643+143: Optical photometry is too red for an isolated DA WD, suggesting an unresolved cool companion (Kidder et al. 1991).

WD1654+160: V824 Her. Pulsating WD (Winget et al. 1984).

WDJ1711+667: WD1711+668. The 2MASS colors do not strongly constrain a spectral type.

WD1717-345: The 2MASS colors do not strongly constrain a spectral type.

WDJ1820+580: WD1819+580.

WD1845+019: Spectroscopic evidence for a long-period, red companion inferred from Hα emission line radial velocities (Maxted & Marsh 1999). It is not known if the close neighbor star described by Debes et al. (2005b) is gravitationally bound to the WD and if it is the same spectroscopic companion star inferred by Maxted & Marsh (1999). Schmidt & Smith (1995) find no sign of a red companion in its optical spectrum (they were not specifically looking for binaries, but noted the possible presence of a red spectral component in several other WDs in their survey for magnetic fields).

WD2009+622: Orbital period of 0.741 d (Ritter & Kolb 2003).

WDJ2013+400: WD2011+395. Orbital period of 0.706 d (Ritter & Kolb 2003).

WDJ2024+200: WD2022+198.

WD2108-431: This object is the one indicated in the University of Arizona White Dwarf Database finding chart, but it is not blue in optical (POSS) images. There is a blue object $\approx 34''$ east, but that object is fuzzy and probably a galaxy.

WD2131+066: IR Peg. Orbital period of 0.164 d (Ritter & Kolb 2003). Pulsating (PG1159 type) WD (MS99). The 2MASS colors do not strongly constrain a spectral type.

Paunzen et al. (1998) suggest that the star observed at $0.3''$ separation is not the binary companion but, rather, the companion is an M dwarf in an even closer, as yet unresolved, orbit.

WD2133+463: Common proper motion ($\mu = 0.46''$ y^{-1}) binary with separation of $a \approx 3''$ (Bakos et al. 2002). Possibly only the red component is detected by 2MASS (e.g., the stellar image doesn't appear elongated in 2MASS images).

WD2154+408: Orbital period of 0.268 d (Ritter & Kolb 2003; also see Hillwig et al. 2002).

WD2237+819: Orbital period of 0.124 d (Ritter & Kolb 2003). Reference for binary status in MS99 is a preprint indicating the Hamburg-Schmidt Survey (e.g., see Gänsicke et al. 2004).

WD2256+249: MS Peg. Orbital period of 0.174 d (Ritter & Kolb 2003).

WD2311-068: Not identified as a binary in Farihi et al. (2005a). This is a cool DQ6 type WD (e.g., Dufour et al. 2005), which might account for its red near-IR colors.

WD2318-137: This is a known common proper motion binary (MS99, Silvestri et al. 2002); there is a co-moving blue object (a WD?) located $\approx 89''$ east of the red star whose 2MASS designation is listed here – this is likely the companion noted in MS99 and (Silvestri et al. 2002). However, the red star appears elongated in the southeast-to-northwest direction on the POSS (red) images, suggesting that it might also be a binary (with separation of $a \approx 3''$). The POSS blue and 2MASS images show the least elongation, suggesting that this closer binary has red and blue components (and possibly only the red component is detected by 2MASS).

WD2326-224: Stellar image is slightly elongated in all POSS images and the combined POSS B+R+IR three-color image shows a color gradient from blue (northwest) to red (southeast). The stellar image is not noticeably elongated in the 2MASS images, and the coordinates of the single 2MASS detection are offset toward the red end of the elongated optical image.

WD2336-187: Believed to be a single WD (Tremblay & Bergeron 2007).

Table 1.   2MASS Photometry for White Dwarfs with Near-IR Excess

WD	2MASS	J	H	K_s
0014+097	00165618+1003591	12.414(25)	11.880(29)	11.602(22)
0017+061	00194100+0624075	13.738(33)	13.189(34)	12.983(32)
0018−267	00213073−2626114	12.504(26)	12.106(25)	12.006(23)
0023+388	00263309+3909044	13.810(26)	13.268(30)	12.939(33)
0027−549	00294996−5441354	9.758(24)	9.129(23)	8.883(23)
0034−211	00372502−2053422	11.454(23)	10.884(21)	10.648(26)
0041+092	00440131+0932578	8.450(34)	7.927(34)	7.805(29)
0104−331	01064686−3253124	14.740(38)	14.162(44)	13.913(57)
0116−231	01183718−2254578	14.640(42)	14.100(37)	13.828(55)
0130−196	01323935−1921394	14.749(37)	14.253(32)	13.997(57)
0131−163	01342407−1607083	12.966(27)	12.468(28)	12.215(30)
0145−705	01461179−7020197	14.962(41)	14.538(63)	14.383(77)
0145−221	01472183−2156512	14.923(32)	14.450(45)	14.335(64)
0148−255J	01480822−2532452	12.412(26)	11.830(21)	11.594(23)
0205+133	02080350+1336256	12.799(22)	12.198(24)	11.961(20)
0208−153	02104280−1506356	12.589(24)	12.057(25)	11.772(25)
0232+035	02350758+0343567	11.265(24)	10.733(21)	10.557(19)
0237+115	02400663+1148280	13.788(30)	13.106(27)	12.892(32)
0248+601	02520803+6019428	13.529(21)	12.894(28)	12.673(29)
0254−053J	02543883−0519509	5.709(19)	5.263(47)	5.090(18)
0255+009.2	02581788+0109458	15.560(63)	14.824(69)	14.526(83)
0257+247	03003606+2453393	12.670(19)	12.070(16)	11.851(21)
0258+184	03011287+1840539	14.991(40)	14.803(67)	14.475(76)
0303−007	03060719−0031144	13.164(24)	12.627(27)	12.405(26)
0302+621	03061669+6222226	15.015(44)	14.989(89)	14.749(95)
0308+096	03105499+0949256	13.723(29)	13.183(31)	12.934(35)
0309−275	03113318−2719260	13.514(26)	12.885(34)	12.731(30)
0312+019	03145212+0206072	15.603(51)	14.998(55)	14.776(98)
0347−137	03501451−1335138	12.080(29)	11.540(29)	11.296(23)
0357+286J	03570582+2837516	9.843(23)	9.275(24)	9.057(17)
0354+463	03581711+4628397	13.594(27)	13.084(38)	12.727(27)
0357−233	03590491−2312243	14.961(44)	14.594(60)	14.256(65)
0357+081	04002668+0814069	14.562(38)	14.343(56)	14.122(57)
0413−077	04152173−0739173	6.747(20)	6.278(40)	5.962(26)
0416+272	04185663+2717484	15.134(38)	15.361(90)	15.065(94)
0419−487	04210556−4839070	10.720(24)	10.148(23)	9.852(25)
0429+176	04322373+1745026	10.753(21)	10.161(19)	9.913(17)
0430+136	04331053+1345134	13.533(21)	12.877(23)	12.634(26)
0458−662	04585395−6628134	13.437(26)	12.727(27)	12.513(29)
0627+299	06303679+2956180	15.128(38)	15.176(71)	14.924(89)
0628−020	06303881−0205537	10.729(27)	10.144(26)	9.857(24)
0710+741	07170975+7400406	14.692(33)	14.423(61)	14.148(65)
0718−316	07204790−3147027	13.253(25)	12.749(26)	12.502(27)
0752−146	07550896−1445506	12.621(24)	12.141(23)	11.837(19)
0800−533	08020022−5327499	13.703(33)	13.186(27)	12.991(27)
0802+387	08055764+3833444	15.336(47)	15.193(79)	14.899(91)

Table 1—Continued

WD	2MASS	J	H	K_s
0805+654	08094545+6518172	14.002(24)	13.449(27)	13.171(31)
0812+478	08154894+4740391	14.587(32)	14.165(41)	13.882(47)
0824+288	08270508+2844024	12.423(28)	11.802(28)	11.650(30)
0852+630	08562826+6250226	12.827(24)	12.122(33)	11.953(21)
0858−220	09005722−2213505	11.348(27)	10.771(24)	10.572(21)
0908+226	09114308+2227488	15.160(40)	14.492(35)	14.389(59)
0915+201	09183291+1953070	15.721(58)	15.166(78)	14.867(80)
0928+399	09315566+3946076	15.049(41)	14.453(58)	14.100(56)
0933+025	09354067+0222005	13.270(24)	12.726(23)	12.477(24)
0937−095	09394969−0945562	14.715(33)	14.135(38)	13.898(48)
0949+451	09522209+4454288	11.924(22)	11.335(16)	11.035(13)
0950+185	09524582+1821026	12.691(22)	12.011(22)	11.786(20)
0956+045	09583717+0421292	14.659(40)	14.131(46)	13.837(59)
1001+203	10040431+2009226	12.640(21)	12.028(21)	11.766(20)
1004−178	10070776−1805246	12.555(22)	11.983(27)	11.745(23)
1013−050	10162867−0520320	10.607(27)	9.990(25)	9.770(23)
1015−173	10172883−1737059	15.238(50)	14.874(58)	14.552(99)
1026+002	10283487−0000295	11.751(24)	11.219(27)	10.943(21)
1027−039	10295925−0413014	15.207(50)	14.611(38)	14.286(71)
1033+464	10362522+4608312	12.564(22)	12.032(24)	11.752(18)
1036−204	10385559−2040572	14.633(33)	14.346(41)	14.035(67)
1037+512	10401680+5056468	13.796(24)	13.261(26)	12.972(26)
1042−690	10441023−6918180	11.423(26)	10.896(27)	10.561(21)
1049+103	10522772+1003380	13.266(29)	12.830(35)	12.483(33)
1055−072	10573517−0731233	13.770(29)	13.680(32)	13.485(38)
1101+364	11043257+3610490	14.832(38)	14.962(70)	14.714(95)
1104+044	11070472+0409077	14.127(33)	13.674(35)	13.509(53)
1106+316	11084306+3123559	15.136(41)	14.524(44)	14.429(86)
1106−211	11091095−2123320	14.676(33)	13.931(39)	13.817(57)
1123+189	11261906+1839178	12.754(23)	12.217(19)	11.990(20)
1126+185	11291804+1816457	12.643(23)	12.166(31)	12.094(23)
1132−298	11352186−3010156	13.799(32)	13.164(29)	12.964(35)
1133+358	11354300+3534235	11.625(19)	11.079(21)	10.802(19)
1136+667	11390593+6630184	12.314(25)	11.695(26)	11.543(23)
1141+504	11434997+5010203	14.779(40)	14.215(43)	13.989(48)
1147+371	11503125+3654159	14.892(39)	14.271(48)	14.114(48)
1156+129	11591564+1239299	14.721(32)	14.099(30)	13.895(42)
1201+437	12042403+4330570	15.393(51)	14.857(68)	13.785(41)
1210+464	12125961+4609467	12.035(23)	11.396(21)	11.161(20)
1213+528	12154411+5231013	9.979(22)	9.340(27)	9.033(21)
1214+032	12165190+0258046	9.234(18)	8.671(22)	8.422(18)
1218+497	12210535+4927207	14.588(38)	14.002(36)	13.837(60)
1224+309	12263089+3038527	15.129(48)	14.669(68)	14.393(77)
1246+299	12484722+2942507	15.055(43)	14.479(55)	14.373(79)
1247−176	12502208−1754465	13.502(24)	12.863(23)	12.601(31)
1255+258J	12553374+2553308	7.370(27)	6.947(51)	6.855(24)

Table 1—Continued

WD	2MASS	J	H	$K_{\rm s}$
1254−133	12563956−1334421	14.499(33)	13.973(51)	13.706(51)
1305+018	13075472+0132106	12.982(26)	12.400(23)	12.144(21)
1307−141	13102255−1427099	13.849(23)	13.226(35)	13.013(36)
1310−305	13134158−3051336	14.931(35)	15.125(53)	14.915(95)
1314+293	13162169+2905548	10.373(19)	9.807(29)	9.565(25)
1319−288	13224044−2905347	12.754(24)	12.271(23)	11.986(23)
1330+793	13303294+7905126	12.506(21)	11.880(23)	11.657(19)
1333+487	13360209+4828472	11.794(23)	11.200(17)	10.927(23)
1340+604J	13410002+6026104	15.555(58)	15.143(74)	14.776(82)
1401+005	14034531+0021359	13.443(23)	12.851(26)	12.771(30)
1412−049	14150220−0511040	13.803(30)	13.092(27)	12.988(34)
1412−109	14150761−1109213	15.379(64)	14.588(66)	14.391(73)
1415+132	14174025+1301487	14.263(36)	13.725(46)	13.553(46)
1424+503	14264410+5006274	10.626(20)	10.008(15)	9.822(22)
1433+538	14344329+5335212	14.667(35)	14.216(50)	13.919(45)
1435+370	14373667+3651378	13.457(24)	12.965(25)	12.746(28)
1436−216	14391264−2150138	13.312(27)	12.770(22)	12.519(29)
1443+336	14460066+3328502	14.284(30)	13.725(30)	13.516(40)
1458+171	15001934+1659146	14.701(31)	14.209(45)	13.847(47)
1501+300	15032075+2952584	14.178(27)	13.745(26)	13.767(53)
1502+349	15043185+3446584	15.231(45)	14.766(61)	14.314(67)
1504+546	15060542+5428186	13.847(25)	13.260(26)	13.001(27)
1517+502	15190599+5007027	15.559(60)	14.746(71)	14.157(72)
1522+508	15242519+5040098	14.757(35)	14.141(45)	13.959(58)
1541−381	15451092−3818515	11.953(25)	11.432(28)	11.190(25)
1558+616	15585553+6132037	14.204(32)	13.600(42)	13.368(42)
1603+125	16053211+1225429	13.552(23)	13.120(23)	12.977(26)
1608+118	16105319+1143538	12.059(22)	11.482(23)	11.260(19)
1610+383	16122147+3812299	14.437(34)	13.807(36)	13.521(42)
1619+525	16202428+5223215	14.168(32)	13.545(35)	13.425(42)
1619+414	16211268+4118093	13.937(21)	13.311(29)	13.025(27)
1622+323	16244899+3217021	14.633(29)	13.963(31)	13.773(39)
1631+781	16291031+7804399	10.975(21)	10.398(21)	10.164(14)
1632−227.1	16352428−2250279	15.279(56)	14.654(75)	14.395(92)
1634−573	16383108−5728112	7.120(23)	6.699(44)	6.571(29)
1643+143	16453913+1417462	12.732(24)	12.125(31)	11.957(24)
1646+062	16490776+0608453	14.035(27)	13.424(30)	13.237(35)
1654+160	16565765+1556254	13.059(29)	12.421(33)	12.129(24)
1711+667J	17112736+6645319	15.120(43)	14.457(57)	14.211(87)
1717−345	17211032−3433286	12.870(39)	12.208(60)	11.940(54)
1820+580J	18202977+5804410	14.058(32)	13.718(35)	13.401(39)
1833+644	18332921+6431520	14.098(30)	13.516(30)	13.241(38)
1845+019	18473908+0157356	12.398(53)	12.014(82)	11.520(47)
1844−654	18490202−6525144	12.703(24)	12.045(26)	11.833(21)
1950+279	19522838+2807527	15.187(48)	14.635(60)	14.527(80)
2009+622	20104287+6225321	14.277(31)	13.915(31)	13.578(48)

Table 1—Continued

WD	2MASS	J	H	K_s
2013+400J	20130936+4002242	13.044(24)	12.520(24)	12.260(32)
2024+200J	20241609+2000474	14.370(33)	13.845(43)	13.595(47)
2101−364	21044692−3615251	14.515(26)	13.915(32)	13.756(38)
2108−431	21113740−4258116	12.773(24)	12.161(23)	11.934(25)
2118−333	21214687−3310477	12.595(24)	11.950(25)	11.734(25)
2131+066	21340822+0650573	15.317(42)	14.723(60)	14.486(92)
2133+463	21351760+4633174	11.297(21)	10.756(17)	10.460(19)
2151−015	21540644−0117102	12.452(29)	11.778(22)	11.414(27)
2154+408	21561824+4102452	12.877(25)	12.383(33)	12.148(27)
2237+819	22371556+8210273	12.824(26)	12.282(32)	11.978(24)
2256+249	22584811+2515439	11.675(20)	11.180(25)	10.915(18)
2311−068	23142520−0632475	14.951(36)	14.942(71)	14.730(93)
2317+268	23200401+2706237	14.609(33)	14.074(36)	13.783(50)
2318−137	23210825−1327465	12.074(22)	11.444(24)	11.174(21)
2326−224	23283886−2210209	12.627(26)	12.035(23)	11.766(21)
2336−187	23385279−1826123	15.057(40)	14.939(63)	14.681(93)

Table 2.   Binary Parameters

WD	Binary Status	References	Spectral Types	$a_{\rm sep}$ ($''$)	Data	References	Comments?
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
0014+097	confirmed	36	WD+dM	$\cdots$	S	36	$\cdots$
			dM2–4	$\lesssim 4$	IP	this work	
0017+061	confirmed	7, 8	DA2+dM4	2.0	IP	8	$\cdots$
			dM0–2.5	$\lesssim 4$	IP	this work	
0018-267	tentative	this work	dG8–K2	$\lesssim 4$	IP	this work	see Appendix A
0023+388	confirmed	43, Papers I & III	WD+dM5.5	$\lesssim 0.025$	IP	Paper III	see Appendix A
			dM3–5	$\lesssim 4$	IP	this work	
0027-549	confirmed	47, 62	DA+dM3	4	IS	47, 62	$\cdots$
			dM1–2.5	$\lesssim 4$	IP	this work	
0034-211	confirmed	8, 43, Papers I & III	WD+dM3.5	0.328	IP	Paper III	see Appendix A
			DA3+dM3	≤ 0.5	IP	8	
			dM1–3	$\lesssim 4$	IP	this work	
0041+092	confirmed	30, 43	DA+dK2	$\lesssim 0.08$	IP	2	see Appendix A
			DA+dK1–3	< 1.9	IPS	30	
			dK3–5	$\lesssim 4$	IP	this work	
0104-331	candidate	this work	dM0–4.5	$\lesssim 4$	IP	this work	$\cdots$
0116-231	confirmed	Papers I & III	WD+dM4.5	1.105	IP	Paper III	see Appendix A
			dM1–5	$\lesssim 4$	IP	this work	
0130-196	candidate	Paper I	dM0–4.5	$\lesssim 4$	IP	this work	see Appendix A
0131-163	confirmed	8, Papers I & III	WD+dM3.5	0.189	IP	Paper III	$\cdots$
			DA1+dM2	≤ 0.5	IP	8	
			dM1–3	$\lesssim 4$	IP	this work	
0145-705	candidate	this work	dG6–dK3	$\lesssim 4$	IP	this work	$\cdots$
0145-221	confirmed	8, Paper I	DA4+dL6	≤ 0.3	IP	8	$\cdots$
			dK1–4	$\lesssim 4$	IP	this work	
J0148-255	confirmed	14, 43, 45, 79, Papers I & III	WD+dM3.5	2.295	IP	Paper III	see Appendix A
			dM1–3	$\lesssim 4$	IP	this work	
			WD+dM3–4	$\lesssim 10$	IP	14	
0205+133	confirmed	15, Papers I & III	WD+dM1	1.257	IP	Paper III	$\cdots$
			dM0–3	$\lesssim 4$	IP	this work	
0208-153	confirmed	Papers I & III	WD+dM2	2.647	IP	Paper III	$\cdots$
			dM2.5–4.5	$\lesssim 4$	IP	this work	
0232+035	confirmed	43, 66	DA+dM	close	S	18, 66	see Appendix A
			dK3–M1	$\lesssim 4$	IP	this work	

Table 2—Continued

WD (1)	Binary Status (2)	References (3)	Spectral Types (4)	$a_{\rm sep}$ ($''$) (5)	Data (6)	References (7)	Comments? (8)
0237+115	confirmed	15, 43, Paper III	WD+dM3 dM0–2	0.124 $\lesssim 4$	IP IP	Paper III this work	$\cdots$
0248+601	candidate	this work	dM0–2	$\lesssim 4$	IP	this work	$\cdots$
J0254-053	confirmed	43, 69	DA+K0 IV DA+K0 IV–III dK0–4 (G5–K0 III)	$\cdots$ $\lesssim 0.08$ $\lesssim 4$	S IP IP	69 2 this work	see Appendix A
0255+009.2	confirmed	51, 60	DA+dM3e dM or M III	close $\lesssim 4$	S IP	60 this work	see Appendix A
0257+247	candidate	this work	dM0–2.5	$\lesssim 4$	IP	this work	see Appendix A
0258+184	tentative	38, this work	$\cdots$	$\lesssim 4$	IP	this work	see Appendix A
0303-007	confirmed	43, Papers I & III, 60	DA+dM2 WD+dM4 dM1–3	close $\lesssim 0.025$ $\lesssim 4$	S IP IP	75, 60 Paper III this work	$\cdots$
0302+621	tentative	this work	$\cdots$	$\lesssim 4$	IP	this work	see Appendix A
0308+096	confirmed	8, 15, 43, 54	DA2+dM4.5 dM1–4	close $\lesssim 4$	IP IP	8 this work	see Appendix A
0309-275	candidate	Paper I	dK7–M0	$\lesssim 4$	IP	this work	$\cdots$
0312+019	candidate	this work	dK5–M5	$\lesssim 4$	IP	this work	see Appendix A
0347-137	confirmed	8, Papers I & III	WD+dM4.5 DA2+dM3 dM1–3	1.052 ≤ 0.5 $\lesssim 4$	IP IP IP	Paper III 8 thiss work	$\cdots$
J0357+286	confirmed	26, 27, 43, Paper I	WD+dK2 dK4–dM2	close $\lesssim 4$	S IP	26, 27 this work	see Appendix A
0354+463	confirmed	8, 43, Paper III	WD+dM7 DA6+dM7 dM4–5.5	$\lesssim 0.025$ ≤ 0.5 $\lesssim 4$	IP IP IP	Paper III 8 this work	$\cdots$
0357-233	confirmed	8, Papers I & III	WD+dM3 DA1+dM3 $\cdots$	1.190 1.2 $\lesssim 4$	IP IP IP	Paper III 8 this work	$\cdots$
0357+081	tentative	this work	$\cdots$	$\lesssim 4$	IP	this work	$\cdots$
0413-077	confirmed	43, Paper I	WD+dM4.5e	≈ 7	I	68, 9	see Appendix A
0416+272	tentative	this work	$\cdots$	$\lesssim 4$	IP	this work	see Appendix A
0419-487	confirmed	3, 42	WD+dM6 WD+dM4	close close	SP S	3 42	see Appendix A

Table 2—Continued

WD	Binary Status	References	Spectral Types	$a_{\rm sep}$ ($''$)	Data	References	Comments?
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
			dM3–4.5	$\lesssim 4$	IP	this work	
0429+176	confirmed	35, 43, Paper I	DA+dM4.5e	close	SP	35	see Appendix A
			dM2–3	$\lesssim 4$	IP	this work	
0430+136	confirmed	43, 75, Paper I	DA+dM	$\cdots$	S	75	$\cdots$
			dM0.5–2.5	~ 4	IP	this work	
0458-662	confirmed	24, 43, Papers I & III	DA+dM2	close	PS	24	see Appendix A
			WD+dM2.5	$\lesssim 0.025$	IP	Paper III	
0627+299	tentative	this work	$\cdots$	$\lesssim 4$	IP	this work	see Appendix A
0628-020	confirmed	43, 47, 62, Paper I	WD+dM	4	IS	47	see Appendix A
			dM2.5–4.5	$\lesssim 4$	IP	this work	
0710+741	confirmed	8, Paper I	DA3+dM7	close	IP	8	see Appendix A
0718-316	confirmed	43, 70	DAO+dM0–2	close	S	70	see Appendix A
0752-146	confirmed	8, Paper I	DA3+dM6	close	IP	8	$\cdots$
0800-533	candidate	77, 29, this work	dM3–4	$\cdots$	P	29	see Appendix A
			dK3–5 or dM2–3	$\lesssim 4$	IP	this work	
0802+387	tentative	this work	$\cdots$	$\lesssim 4$	IP	this work	see Appendix A
0805+654	confirmed	36	WD+dM	$\cdots$	S	36	$\cdots$
			dM2–4	$\lesssim 4$	IP	this work	
0812+478	candidate	Paper I	$\cdots$	$\lesssim 4$	IP	this work	$\cdots$
0824+288	confirmed	8, 15, 36, 43	DA1+dC+dM3.5	$\leq 0.5, 3.3$	IP	8	$\cdots$
			dK6–M1	$\lesssim 4$	IP	this work	
0852+630	candidate	this work	$\cdots$	$\lesssim 4$	IP	this work	see Appendix A
0858-220	confirmed	43, 55, 61	DC+dM	5	IPS	55	see Appendix A
			dK5–M2	~ 4	IP	this work	
0908+226	candidate	43, Paper I	late dK	$\lesssim 4$	IP	this work	see Appendix A
0915+201	confirmed	Paper I, this work	mid dK – late dM	$\lesssim 4$	IP	this work	see Appendix A
0928+399	confirmed	60	DA+dM3e	close	S	60	$\cdots$
			dM3–8	$\lesssim 4$	IP	this work	
0933+025	confirmed	8, 15, 36, 43	DA2+dM3.5	≤ 0.5	IP	8	$\cdots$
			dM2–3	$\lesssim 4$	IP	this work	
0937-095	candidate	Paper I	dK4–M4	$\lesssim 4$	IP	this work	see Appendix A
0949+451	confirmed	Paper III	WD+dM4.5	2.892	IP	Paper III	see Appendix A
			dM3–4.5	$\lesssim 4$	IP	this work	

Table 2—Continued

WD	Binary Status	References	Spectral Types	$a_{\rm sep}$ ($''$)	Data	References	Comments?
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
0950+185	confirmed	8, 15, 36, 43	DA2+dM2	1.1	IP	8	$\cdots$
			dM0–1	$\lesssim 4$	IP	this work	
0956+045	confirmed	8, 15, 43	DA3+dM4.5	2.0	IP	8	$\cdots$
			dM2–5.5	$\lesssim 4$	IP	this work	
1001+203	confirmed	8, 15, 36, 43, Paper I	DA2+dM3	≤ 0.5	IP	8	$\cdots$
			dM1–3.5	$\lesssim 4$	IP	this work	
1004-178	candidate	this work	dM0.5–3	$\lesssim 4$	IP	this work	$\cdots$
1013-050	confirmed	8, 43, Paper I	DAO1+dM4.5+dM1+dM1	close, 3.2, 3.2	IP	8	see Appendix A
			dM0–2.5	$\lesssim 4$	IP	this work	
1015-173	candidate	Paper I	$\cdots$	$\lesssim 4$	IP	this work	$\cdots$
1026+002	confirmed	8, 15, 36, 43, 54, Paper I	DA3+dM4e	close	S	54	see Appendix A
			DA3+dM4.5	close	IP	8	
			dM2.5–4	$\lesssim 4$	IP	this work	
1027-039	candidate	this work	dM2–7	$\lesssim 4$	IP	this work	see Appendix A
1033+464	confirmed	8, 14, 15, 36, 43	DA2+dM4.5	≤ 0.5	IP	8	$\cdots$
			dM2.5–4	$\lesssim 4$	IP	this work	
			WD+dM4–5	$\lesssim 10$	IP	14	
1036-204	tentative	Paper II, this work	$\cdots$	$\lesssim 4$	IP	this work	see Appendix A
1037+512	confirmed	36, Paper I	WD+dM	$\cdots$	S	36	$\cdots$
			dM2.5–4.5	$\lesssim 4$	IP	this work	
1042-690	confirmed	8, 44	DA2+dM4.5	close	IP	8	see Appendix A
			dM4–5	$\lesssim 4$	IP	this work	
1049+103	confirmed	8, 15, 36, 43	DA2+dM4	≤ 0.5	IP	8	$\cdots$
			$\cdots$	$\lesssim 4$	IP	this work	
1055-072	tentative	this work	$\cdots$	$\lesssim 4$	IP	this work	see Appendix A
1101+364	tentative	this work	$\cdots$	$\lesssim 4$	IP	this work	see Appendix A
1104+044	confirmed	this work	WD+dK0–4	≈ 3	IP	this work	see Appendix A
1106+316	candidate	Paper I	dK5–M0	$\lesssim 4$	IP	this work	$\cdots$
1106-211	tentative	Paper I	$\cdots$	$\lesssim 4$	IP	this work	see Appendix A
1123+189	confirmed	8, 15, 43, 56, Paper I	DA1+dM3	1.3	IP	8	$\cdots$
			dM2–3	$\lesssim 4$	IP	this work	
			DA4+dM	$\cdots$	S	56	
1126+185	tentative	15, 49	DC8+dG–K	$\cdots$	S	49	see Appendix A

Table 2—Continued

WD (1)	Binary Status (2)	References (3)	Spectral Types (4)	$a_{\rm sep}$ ($''$) (5)	Data (6)	References (7)	Comments? (8)
			dK1–4	$\lesssim 4$	IP	this work	
1132-298	confirmed	43, 53	DA+dM4	close	S	53	see Appendix A
			dK7–M2	$\lesssim 4$	IP	this work	
1133+358	confirmed	17, 43, 49, Paper I	DC+dM4.5e	$\cdots$	S	49	$\cdots$
			dM2.5–4	$\lesssim 4$	IP	this work	
1136+667	confirmed	21, 23, 43, 63, Paper I	DAO+dMe	close	S	23	see Appendix A
			DAO+dK7	close	S	63	
			dK6–M0	$\lesssim 4$	IP	this work	
1141+504	confirmed	15, 60	DA+dM4e	close	S	60	$\cdots$
			dK3–M3.5	$\lesssim 4$	IP	this work	
1147+371	candidate	this work	dK5–M2.5	$\lesssim 4$	IP	this work	$\cdots$
1156+129	tentative	Paper I	dK6–M2.5	$\lesssim 4$	IP	this work	see Appendix A
1201+437	tentative	12, 15, 43, Paper I	DC+dMe	$\cdots$	$\cdots$	12	see Appendix A
			$\cdots$	$\lesssim 4$	IP	this work	
1210+464	confirmed	8, 15, 36, 43, Paper I	DA2+dM2	≤ 0.5	IP	8	$\cdots$
			dM0–2	$\lesssim 4$	IP	this work	
1213+528	confirmed	34, 43, 50	DA+dM2	close	S	34	see Appendix A
			dM3–5	$\lesssim 4$	IP	this work	
			DA+dM4.5e	$\cdots$	P	50	
1214+032	confirmed	43, 55, 62, Paper I	DA+sdM3	2	IS	55, 62	$\cdots$
			dM2–3	$\lesssim 4$	IP	this work	
1218+497	confirmed	60, Papers I & III	WD+dM4	0.302	IP	Paper III	$\cdots$
			DA+dM4e	close	S	60	
			dK4–M2	$\lesssim 4$	IP	this work	
1224+309	confirmed	15, 46, Paper I	DA+dM4+	close	PS	46	see Appendix A
1246+299	candidate	this work	dK3–M0	$\lesssim 4$	IP	this work	$\cdots$
1247-176	confirmed	32, 33, Paper I	DA+dMe	close	S	32, 33	see Appendix A
			dM1–3	$\lesssim 4$	IP	this work	
J1255+258	confirmed	10, 43	sdO+G5 III	close	S	10, 25	see Appendix A
			$\cdots$	$\lesssim 0.05$	I	5	
			G3–K0 III	$\lesssim 4$	IP	this work	
1254-133	candidate	this work	dM0–5	$\lesssim 4$	IP	this work	$\cdots$
1305+018	confirmed	4, this work	dM1–3.5	$\lesssim 2$	IP	this work	see Appendix A
1307-141	candidate	Paper I	dK7–M2.5	$\lesssim 4$	IP	this work	$\cdots$

Table 2—Continued

WD (1)	Binary Status (2)	References (3)	Spectral Types (4)	$a_{\rm sep}$ ($''$) (5)	Data (6)	References (7)	Comments? (8)
1310-305	tentative	this work	$\cdots$	$\lesssim 4$	IP	this work	see Appendix A
1314+293	confirmed	36, 39	DAwk+dM3.5e dM0.5–3	3 $\lesssim 4$	IPS IP	39 this work	see Appendix A
1319-288	confirmed	33	DA+dM	$\cdots$	S	33	$\cdots$
1330+793	confirmed	Paper I	dM0–2	≈ 3.9	IP	this work	see Appendix A
1333+487	confirmed	16, 43, Papers I & III	WD+dM5 DB+dM dM2–4	2.947 "unresolved visually" $\lesssim 4$	IP PS IP	Paper III 16 this work	$\cdots$
J1340+604	confirmed	43, 60, Paper III	WD+dM4 DA+dM3e	$\lesssim 0.025$ close	IP S	Paper III 60	see Appendix A
1401+005	candidate	this work	dK5+	$\lesssim 4$	IP	this work	$\cdots$
1412-049	confirmed	Papers I & III	WD+dM0	3.508	IP	Paper III	$\cdots$
1412-109	confirmed	this work	K8–M5 III	$\lesssim 4$	IP	this work	see Appendix A
1415+132	confirmed	11, 19	DA+dM3+ dK3–M2	close $\lesssim 4$	S IP	11 this work	$\cdots$
1424+503	confirmed	43, 59	DA2+dM dK7–M2.5	close $\lesssim 4$	S IP	59 this work	see Appendix A
1433+538	confirmed	15, 43, 60, Paper III	DA+dM4 WD+dM5 DA2+dM4.5	close $\lesssim 0.025$ ≤ 0.5	S IP IP	60 Paper III 8	see Appendix A
1435+370	confirmed	Papers I & III	WD+dM2.5	1.251	IP	Paper III	$\cdots$
1436-216	confirmed	78, Paper I	DA+dM dM2–3.5	$\cdots$ $\lesssim 4$	S IP	78 this work	$\cdots$
1443+336	confirmed	15, 36, Papers I & III	WD+dM2.5 dK4–M3	0.679 $\lesssim 4$	IP IP	Paper III this work	see Appendix A
1458+171	confirmed	Papers I & III	WD+dM5 dM4–5.5	$\lesssim 0.025$ $\lesssim 4$	IP IP	Paper III this work	$\cdots$
1501+300	tentative	this work	$\cdots$	$\lesssim 4$	IP	this work	see Appendix A
1502+349	confirmed	Papers I & III	WD+dM5	1.913	IP	Paper III	$\cdots$
1504+546	confirmed	Papers I & III	DA+dMe WD+dM4 dM1–4	$\cdots$ $\lesssim 0.025$ $\lesssim 4$	S IP IP	65 Paper III this work	$\cdots$
1517+502	confirmed	37, 43, 60, Papers I & III	DA+dCe	close	S	60	see Appendix A

Table 2—Continued

WD	Binary Status	References	Spectral Types	$a_{\rm sep}$ ($''$)	Data	References	Comments?
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
			WD+dC	$\lesssim 0.025$	IP	Paper III	
			dM9–L	$\lesssim 4$	IP	this work	
1522+508	confirmed	60, Paper I	DA+dM4e	close	S	60	$\cdots$
			dK5–M3	$\lesssim 4$	IP	this work	
1541-381	tentative	this work	$\leq$dM3	$\lesssim 4$	IP	this work	see Appendix A
1558+616	confirmed	43, Papers I & III	WD+dM4.5	0.715	IP	Paper III	see Appendix A
			dK5–M3.5	$\lesssim 4$	IP	this work	
1603+125	confirmed	Papers I & III	WD+dK3	$\lesssim 0.025$	IP	Paper III	see Appendix A
			dK0–4	$\lesssim 4$	IP	this work	
1608+118	confirmed	8	DA2+dM3	3.0	IP	8	see Appendix A
			dM0–2.5	$\lesssim 4$	IP	this work	
1610+383	confirmed	Paper I, this work	WD+dM1–5	≈ 4	IP	this work	see Appendix A
1619+525	confirmed	Papers I & III	WD+dM+dM	0.466, 2.596	IP	Paper III	see Appendix A
			dK6–M0	$\lesssim 4$	IP	this work	
1619+414	confirmed	43, 74, Papers I & III	WD+dM5	0.231	IP	Paper III	$\cdots$
			dM2–4.5	$\lesssim 4$	IP	this work	
			DA+dM	$\cdots$	S	74	
1622+323	confirmed	11, 15, 36, 43, Papers I & III	WD+dM1	0.094	IP	Paper III	see Appendix A
			dM0–1	$\lesssim 4$	IP	this work	
1631+781	confirmed	6, 8, 43, 64, Papers I & III	WD+dM3+dM3	0.007, 0.163	IP	Paper III	see Appendix A
			DA+dM2–5	close	IS	6	
			DA2+dM4–5e	close	S	64	
			DA1+dM3	≤ 0.5	IP	8	
			dM1–3	$\lesssim 4$	IP	this work	
1632-227.1	candidate	this work	late dK – late dM	$\lesssim 4$	IP	this work	see Appendix A
1634-573	confirmed	48, 72	DO+dK0	2.35	S	48, 72	see Appendix A
			dG9–K5	$\lesssim 4$	IP	this work	
1643+143	confirmed	8, 11, 31, 36, 58, Paper I	DA2+dM2	≤ 0.5	IP	8	see Appendix A
			dK5–M0.5	$\lesssim 4$	IP	this work	
1646+062	confirmed	15, 36, 43, Paper III	WD+dM3.5	0.163	IP	Paper III	$\cdots$
			dK5–M2	$\lesssim 4$	IP	this work	
1654+160	confirmed	8, Paper I	DB2+dM4.5	3.50	IP	8	see Appendix A
			dM2–5	$\lesssim 4$	IP	this work	
J1711+667	confirmed	14, Paper I	WD+dM5–5.5	≈ 2.5	IP	14	see Appendix A
			late dK – late dM	$\lesssim 4$	IP	this work	

Table 2—Continued

WD (1)	Binary Status (2)	References (3)	Spectral Types (4)	$a_{\rm sep}$ ($''$) (5)	Data (6)	References (7)	Comments? (8)
1717-345	confirmed	28, Paper I	DA+M3.5e late dK – late dM	$\cdots$ $\lesssim 4$	S IP	28 this work	see Appendix A
J1820+580	candidate	14	WD+dM5.5–6	$\lesssim 10$	IP	14	see Appendix A
1833+644	confirmed	43, 73	DA+dM dM1–4.5	$\cdots$ $\lesssim 4$	S IP	73 this work	$\cdots$
1845+019	candidate	7, 41	WD+dM	≈ 3	IP	7	see Appendix A
1844-654	candidate	this work	dM0–2	$\lesssim 4$	IP	this work	$\cdots$
1950+279	candidate	this work	dK4–M1	$\lesssim 4$	IP	this work	$\cdots$
2009+622	confirmed	8, 43, Paper III	DA2+dM5 WD+dM4.5	close $\lesssim 0.025$	IP IP	8 Paper III	see Appendix A
J2013+400	confirmed	43, 67, 71	DAO+M3 DAO+M4–5 dM2.5–4	close close $\lesssim 4$	S S IP	67 71 this work	see Appendix A
J2024+200	confirmed	11, 40, 43	DA+dM dM0–4.5	$\cdots$ $\lesssim 4$	S IP	11, 40 this work	see Appendix A
2101-364	candidate	this work	dK5–M0.5	$\lesssim 4$	IP	this work	$\cdots$
2108-431	tentative	this work	dM0–2.5	$\lesssim 4$	IP	this work	see Appendix A
2118-333	candidate	this work	dM0–2	$\lesssim 4$	IP	this work	$\cdots$
2131+066	confirmed	8, 15, 43, 52, 76	DO1+dM3 WD+dM1–3 WD+dK5–M0 mid dK – mid dM	0.3 0.3 $\cdots$ $\lesssim 4$	IP IP S IP	8 52 76 this work	see Appendix A
2133+463	confirmed	1, 43, Paper I	dM3–4.5	≈ 3	IP	this work	see Appendix A
2151-015	confirmed	20, 41, 43, 78, Papers I & III	WD+dM8 DA6+dM8 dM7–8.5	1.082 ≤ 0.5 $\lesssim 4$	IP IP IP	Paper III 8 this work	$\cdots$
2154+408	confirmed	8, 22	DA2+dM3.5	close	IP	8	see Appendix A
2237+819	confirmed	13, 43	WD+dM3–4 dM3–5	close $\lesssim 4$	PS IP	13 this work	see Appendix A
2256+249	confirmed	8, 43, 57, Paper I	DA2+dM4 DA2+M3–5	close close	IP PS	8 57	see Appendix A
2311-068	tentative	this work	$\cdots$	$\lesssim 4$	IP	this work	see Appendix A
2317+268	confirmed	Papers I & III	WD+dM3.5	$\lesssim 0.025$	IP	Paper III	$\cdots$

Table 2—Continued

WD (1)	Binary Status (2)	References (3)	Spectral Types (4)	a_{sep} ($''$) (5)	Data (6)	References (7)	Comments? (8)
			dM2–5	$\lesssim 4$	IP	this work	
2318-137	tentative	this work	dM1–4	≈ 3	IP	this work	see Appendix A
2326-224	confirmed	Paper I, this work	dM1–4	≈ 4	IP	this work	see Appendix A
2336-187	tentative	Paper I	$\cdots$	≈ 4	IP	this work	see Appendix A

References. — (1) Bakos et al. (2002), (2) Barstow et al. (2001), (3) Bruch & Diaz (1998), (4) Cheselka et al. (1993), (5) Ciardullo et al. (1999), (6) Cooke et al. (1992), (7) Debes et al. (2005b), (8) Farihi et al. (2005a), (9) Feibelman (1986), (10) Feibelman & Kaler (1983), (11) Finley et al. (1997), (12) Fleming et al. (1993), (13) Gänsicke et al. (2004), (14) Green et al. (2000), (15) Green et al. (1986), (16) Greenstein (1975), (17) Greenstein (1976), (18) Greenstein (1984), (19) Greenstein (1986), (20) Greenstein & Liebert (1990), (21) Heber et al. (1996), (22) Hillwig et al. (2002), (23) Holberg et al. (2001), (24) Hutchings et al. (1995), (25) Jasniewicz et al. (1996), (26) Jeffries et al. (1996), (27) Jeffries & Smalley (1996), (28) Kawka et al. (2004), (29) Kawka et al. (2007), (30) Kellett et al. (1995), (31) Kidder et al. (1991), (32) Kilkenny et al. (1997), (33) Koester et al. (2001), (34) Lanning (1982), (35) Lanning & Pesch (1981), (36) Liebert et al. (2005), (37) Liebert et al. (1994), (38) Lisker et al. (2005), (39) Margon et al. (1976), (40) Mason et al. (1995), (41) Maxted & Marsh (1999), (42) Maxted et al. (2007), (43) McCook & Sion (1999), (44) Morales-Rueda et al. (2005), (45) Mueller & Bues (1987), (46) Orosz et al. (1999), (47) Oswalt et al. (1988), (48) Parsons et al. (1976), (49) Putney (1997), (50) Probst (1983), (51) Raymond et al. (2003), (52) Reed et al. (2000), (53) Ruiz & Maza (1990), (54) Saffer et al. (1993), (55) Salim & Gould (2003), (56) Schmidt & Smith (1995), (57) Schmidt et al. (1995). (58) Schultz et al. (1996), (59) Schwartz et al. (1995), (60) Silvestri et al. (2006), (61) Silvestri et al. (2002), (62) Silvestri et al. (2001), (63) Sing et al. (2004), (64) Sion et al. (1995), (65) Stepanian et al. (2001), (66) Thorstensen et al. (1978), (67) Thorstensen et al. (1994), (68) van den Bos (1926), (69) Vennes et al. (1995), (70) Vennes & Thorstensen (1994), (71) Vennes et al. (1999), (72) Wegner (1979), (73) Wegner & McMahan (1988), (74) Wegner & Swanson (1990b), (75) Wegner et al. (1987), (76) Wesemael et al. (1985), (77) Wickramasinghe & Bessell (1977), (78) Zuckerman et al. (2003), (79) Zwitter & Munari (1995)

Table 3.   White Dwarf Statistics

Category	Status in this work: Total	Confirmed	Candidate	Tentative
This work totals	154	105	28	21
New to this work	83	46	20	17
Candidate in Paper I[a]	68	58	7	3
Tentative in Paper I[b]	3	1	1	1

[a]Table 1 in Paper I.

[b]Table 2 in Paper I.

Table 4.   Absolute Magnitudes of Low Mass Stars

Spectral Type	Absolute Magnitude[a]			Maximum Distance Modulus[b]		
	M_J	M_H	$M_{K_{\rm s}}$	$(m-M)_J$	$(m-M)_H$	$(m-M)_{K_{\rm s}}$
M0	6.45	5.82	5.62	9.35	9.28	8.67
M1	6.72	6.11	5.88	9.08	8.99	8.41
M2	6.98	6.38	6.14	8.82	8.72	8.16
M3	7.24	6.68	6.40	8.56	8.42	7.90
M4	8.34	7.80	7.50	7.46	7.30	6.80
M5	9.44	8.88	8.54	6.36	6.22	5.76
M6	10.18	9.54	9.15	5.62	5.56	5.15
M7	10.92	10.29	9.89	4.88	4.81	4.41
M8	11.14	10.46	10.05	4.66	4.64	4.24
M9	11.43	10.71	10.26	4.37	4.39	4.04
L0	11.72	10.90	10.32	4.08	4.20	3.98
L1	12.00	11.20	10.57	3.80	3.90	3.73
L2	12.29	11.28	10.58	3.51	3.82	3.72
L3	12.58	11.54	10.86	3.22	3.56	3.44
L4	12.87	11.68	11.00	2.93	3.42	3.30
L5	13.16	11.99	11.29	2.64	3.11	3.01
L6	14.31	13.13	12.25	1.49	1.97	2.05
L7	14.45	13.27	12.51	1.35	1.83	1.79
L8	14.58	13.34	12.62	1.22	1.76	1.68
WD[c]	13.19(57)	13.12(50)	13.06(48)	2.61	1.98	1.24

[a]From   Bessell & Brett   (1988);   Gizis et al.   (2000);   Kirkpatrick et al.   (2000); Hawley et al. (2002).

[b]For 2MASS Good detection limits of $J_{\rm lim} = 15.8$, $H_{\rm lim} = 15.1$, and $K_{\rm s,lim} = 14.3$.

[c]Average photometry from the single WD sample used in the Paper I simulation.
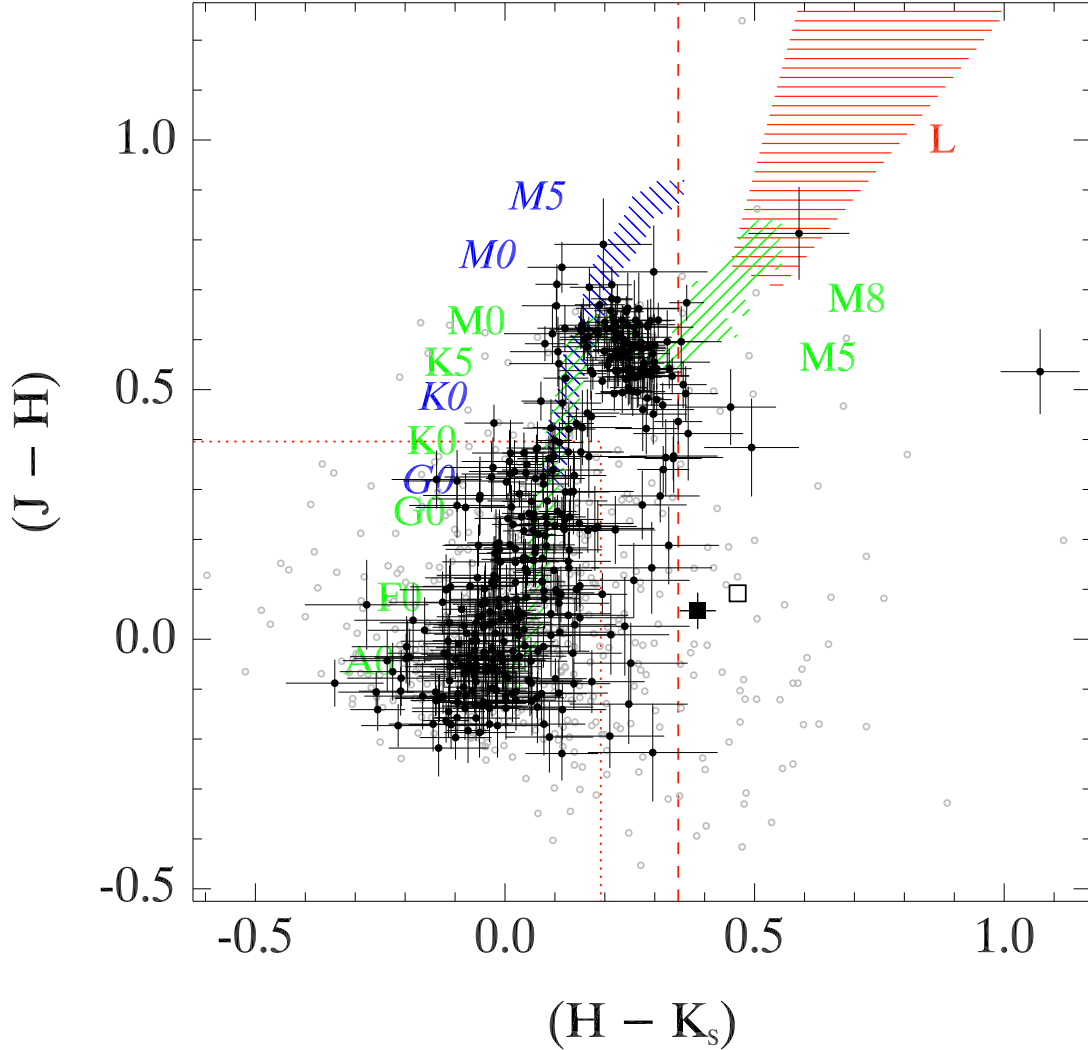
Fig. 1.— Near-IR color-color diagram for the WDs from MS99 that are detected in the 2MASS All Sky Data Release. Filled black points with 1σ error bars are the Good detections. Unfilled grey points are the Moderate detections. (Poor detections are not shown, except as noted below.) The squares are the two known WDs with circumstellar dust disks: WD2326+049 (G29-38; filled square, Good detection) and WD1729+371 (GD362; unfilled square, Poor detection). The cross-hatched regions show the loci of empirical mean 2MASS colors (Bessell & Brett 1988; Gizis et al. 2000; Kirkpatrick et al. 2000; Hawley et al. 2002; transformed from other photometric systems using the relations in Carpenter 2001 when necessary) of the main sequence (///; green in the electronic edition), giant branch (\ \ \; blue in the electronic edition) and L dwarfs (horizontal cross-hatches; red in the electronic edition). Spectral types are labeled at the correct $(J - H)$ value, but offset in $(H - K_s)$; spectral types of the main sequence and L dwarfs are labeled with roman font, while those of giants are labeled with italic font. The dotted lines (red in the electronic edition) mark the boundary between "normal" WDs and red-excess WDs. The vertical dashed line (red in the electronic edition) marks the $(H - K_s)$ color of a dM5 star for comparison.
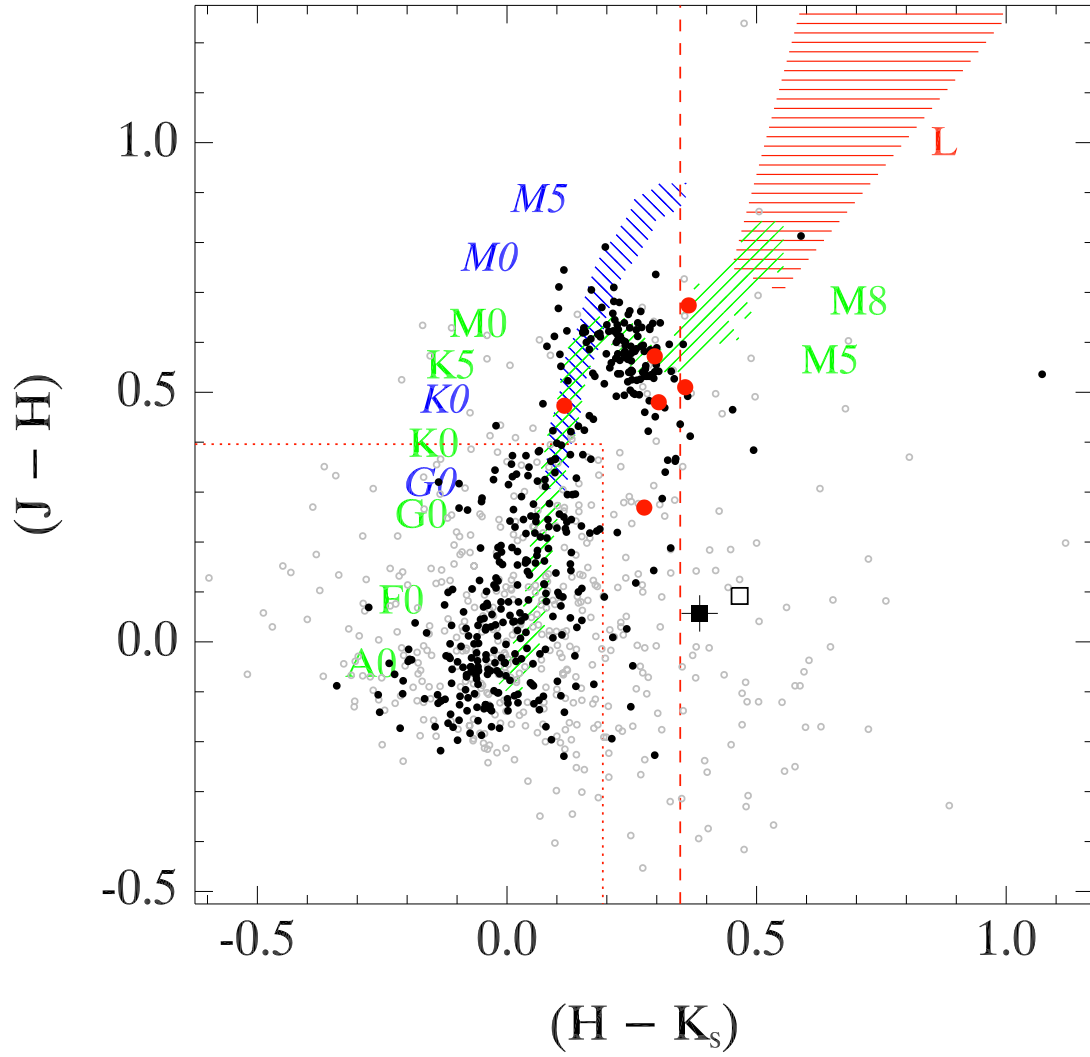
Fig. 2.— As in Figure 1, but, for clarity, the error bars have not been plotted. The six objects discussed in §3.2.2 are plotted with large symbols (red in the electronic edition).