THE WIRED SURVEY. IV. NEW DUST DISKS FROM THE MCCOOK & SION WHITE DWARF CATALOG

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ABSTRACT

We have compiled photometric data from the Wide-field Infrared Survey Explorer All Sky Survey and other archival sources for the more than 2200 objects in the original McCook & Sion Catalog of Spectroscopically Identified White Dwarfs. We applied color-selection criteria to identify 28 targets whose infrared spectral energy distributions depart from the expectation for the white dwarf (WD) photosphere alone. Seven of these are previously known WDs with circumstellar dust disks, five are known central stars of planetary nebulae, and six were excluded for being known binaries or having possible contamination of their infrared photometry. We fit WD models to the spectral energy distributions of the remaining ten targets, and find seven new candidates with infrared excess suggesting the presence of a circumstellar dust disk. We compare the model dust disk properties for these new candidates with a comprehensive compilation of previously published parameters for known WDs with dust disks. It is possible that the current census of WDs with dust disks that produce an excess detectable at K-band and shorter wavelengths is close to complete for the entire sample of known WDs to the detection limits of existing near-IR all-sky surveys. The WD dust disk candidates now being found using longer wavelength infrared data are drawn from a previously underrepresented region of parameter space, in which the dust disks are overall cooler, narrower in radial extent, and/or contain fewer emitting grains.

Key words: circumstellar matter – planetary systems – surveys – white dwarfs

Online-only material: color figure

1. INTRODUCTION

Dust disks are common in a wide variety of astrophysical situations, including the central engines of quasars and active galactic nuclei (e.g., Rowan-Robinson 1977; Antonucci 1993), the precursors of planetary system formation around protostars (e.g., Natta 2008) and post-formation debris around young stars (e.g., Aumann 1985; Chini et al. 1991), and even the recently discovered largest ring of Saturn (e.g., Verbiscer et al. 2009). The first dust disk around a white dwarf (WD), G29-38, was discovered by virtue of its infrared (IR) excess over the WD photosphere (Zuckerman & Becklin 1987), although it took another decade to cast aside all doubts that the excess was truly due to dust and not an unresolved brown dwarf companion (Koester et al. 1997; Kuchner et al. 1998). Debes & Sigurdsson (2002) and Jura (2003) developed a model for the origin of WD dust disks involving tidal disruption of a comet or asteroid perturbed into the WD Roche lobe due to the gravitational influence of a remnant planetary system containing at least one massive planet (Debes et al. 2012). It was not until 2005 that the second WD with a dust disk, GD 362, was discovered (Becklin et al. 2005; Kilic et al. 2005). By the end of 2010, 20 dusty WDs were known (Table 5.1 in Farihi 2011), largely owing to sensitive IR observations from the Spitzer Space Telescope. Predating the discovery of dust around WDs, it was known that a small fraction of WDs show absorption lines of metals in their optical and UV photospheric spectra (e.g., Lacombe et al. 1983; Shipman & Greenstein 1983; Zeidler-K.T. et al. 1986). These lines originate from “pollution” of a WD’s geometrically thin, high density (but non-degenerate) atmosphere, which in most objects is otherwise pure hydrogen or helium. Gravitational settling times in hydrogen-rich (DA) WD atmospheres are very short (a few days to \( \lesssim 1000 \) yr), so metals quickly diffuse out of the photosphere unless replenished. Thus, the observed metals were thought to be supplied by ongoing accretion from the interstellar medium (ISM; Sion et al. 1990). This explanation was problematic; notably, the required accretion rate is high (\( \gtrsim 10^{-8} \) g s\(^{-1}\)) compared to \( \sim 10^{-7} \) g s\(^{-1}\) expected from ISM accretion and it is difficult to explain the relative elemental abundances of the accreted material, which do not match equilibrium ISM values (see Farihi et al. 2010a and the review and discussion in Sections 5.2.4 and 5.6.6 of Farihi 2011).

It is a testament to the strength of the asteroid disruption model for WD dust disks that it also explains the metal-rich WDs, via accretion from circumstellar dust. Zuckerman et al. (2007) showed that the relative abundances of accreted metals in the dusty WD GD 362 closely match those of the terrestrial planets. Analyses of two metal polluted WDs (GD 61, NLTT 43806) suggest that the accreted dust was derived from an asteroid whose origin was in the outer layers of a differentiated planet, in which the heaviest elements had sunk to the core, leaving a lithosphere rich in Ca and possibly water (Farihi et al. 2011; Zuckerman et al. 2011). Thus, observing WDs with dust disks is directly linked to determining how the chemical diversity of planetary systems can influence the probability that some planets support life.

In order to facilitate this, a large sample of WDs with dust disks is desired. Consequently, we have been carrying out the WISE InfraRed Excesses around Degenerates (WIRED) Survey, utilizing photometry from the Wide-field Infrared Survey Explorer (WISE), a NASA medium class Explorer mission launched on 2009 December 14 (Wright et al. 2010). WISE
map the entire sky at 3.4, 4.6, 12, and 22 μm (W1, W2, W3, and W4 bands, respectively) with 5σ point source sensitivities of approximately 0.08, 0.11, 1, and 6 mJy, respectively. Complete sky coverage was achieved in 2010 mid-July. The WIRED Survey has the goals of characterizing WD stars in the WISE bands, confirming objects known to have IR excess from past observations (Spitzer, 2MASS, UKIDSS, etc.), and revealing new examples of WDs with IR excess that can be attributed to unresolved companions or circumstellar debris disks. We are utilizing target lists drawn from cataloged WD samples (e.g., from the Sloan Digital Sky Survey, SDSS; McCook & Sion; etc.). To date, we have published results from WIRED for the SDSS WD sample that have nearly tripled the number of known WDs with circumstellar dust disks and increased the number of WD + brown dwarf binaries by almost an order of magnitude. We now present initial results from examining the McCook & Sion (1999, henceforth, MS99) catalog of spectroscopically identified WDs, which resulted in the new identification of seven WDs with IR excess indicating the likely presence of a circumstellar dust disk.

2. TARGETS AND DATA

MS99 contains 2249 (optical) spectroscopically identified WDs. The updated and online version of MS99, the Villanova University White Dwarf Catalog7 (henceforth, MSonline), currently contains over 14,000 entries. For our purposes, we have used only those targets contained in the original print publication of MS99 (most of the new WDs listed in MSonline are objects discovered by SDSS and are covered in our previous WIRED paper; see Debes et al. 2011b). Since the publication of MS99, a number of the WDs were subsequently reclassified as non-WDs (e.g., quasars) or nonexistent (e.g., some WDs are listed twice in MS99 with different names, such as WD 2321 – 549 = WD J2324 – 546), leaving 2202 viable targets. To further narrow the target list, we considered only the 1474 WDs from MS99 for which Hoard et al. (2007) found Two Micron All Sky Survey (2MASS) near-IR detections.

As a first pass at identifying IR-bright (or otherwise “interesting”) WDs from this input list, we utilized the following selection criteria for each target: (1) 2MASS-J, W1, and W2 photometry exists, (2) the WISE color index (W1 – W2) ≥ +0.3 mag, and (3) the signal-to-noise ratios (S/Ns) of the W1 and W2 detections are both ≥7.

The IR color–color diagram of the MS99 WDs (see Figure 1) demonstrates that the second criterion selects the majority of known dusty WDs, while avoiding the bulk of the “uninteresting” WDs. The third criterion excludes color-selected targets whose redness is spurious, resulting from low S/N photometry. A broad 10 μm silicate emission feature is a hallmark of circumstellar dust around WDs (Jura et al. 2009) and falls into the W3 band. In principle, this could offer an additional selection criterion for identifying WDs with dust. In practice, however, we found that due to the lower sensitivity of WISE in the W3 band compared to W1 and W2 (cf, while 67% and 58% of our input sample have a W1 and/or W2 detection, respectively, only 16% have a W3 detection), almost 92% of the targets that have a cataloged W3 detection are already selected by our 1st criterion. Only two of the targets with a W3 detection that were not selected by our 1st criterion have S/N ≥ 7 in W3, and both of them are unusable: WD 1919+145 is contaminated by a nearby source (Mullally et al. 2007) and WD 2110+300 is in an unresolved binary with a G-type giant star (ζ Cygni; Griffin & Keenan 1992). In addition, closer inspection of the WISE images of our targets shows that as many as ~50% of the cataloged W3 “detections” (especially at low S/N) are probably unreliable (e.g., due to bright, structured background or nearby sources) and should be treated as upper limits (e.g., see Section 2.1).

Incidentally, there are some features of the IR color–color diagram that we will not discuss in detail, but are worth noting.

1. There are two principal loci of WDs (plotted as small gray circles): a large one centered around (J – W1) ~ +0.25 mag, (W1 – W2) ~ 0 mag, and a smaller one at (J – W1) ~ +1.0 mag, (W1 – W2) ~ +0.2 mag. The former is the locus of “naked” WDs, while the latter is the locus of unresolved binaries containing a WD and a low mass main sequence star. We found a similar distribution of the majority of points in the r, i, J, W1, W2 color–color planes for the targets selected from the SDSS Data Release 7 preliminary WD catalog (Debes et al. 2011b).

2. The known WDs with circumstellar dust disks form a broad sequence extending from the locus of naked WDs (with blue colors) to the upper right (red) corner of the color–color diagram. The new candidate WDs with dust disks reported

Figure 1. Infrared color–color diagram of MS99 WDs with 2MASS J and WISE W1 and W2 detections. The vertical dashed line marks a (W1 – W2) color of +0.3 mag, which was used in the target selection process. Representative color index error bars are shown in the upper left; from top to bottom, 25%, 50%, 75%, and 90% of the detected targets have photometric uncertainties smaller than the indicated error bars. The points are symbol-coded as follows: new candidate WDs with dust disks (filled circles), selected targets that are not dust disk candidates (unfilled circles), known WDs with dust disks that are in (unfilled squares) or not in (filled squares) MS99, known unresolved binaries (diamonds), central stars of planetary nebulae (downward facing triangles), WISE photometry is contaminated (upward facing triangles), and remaining WDs that did not satisfy our selection criteria as targets-of-interest (small gray circles). WD 1201+437 is also a known unresolved binary with (J – W1) = +3.8 mag and, for clarity, is the only target not plotted here. (A color version of this figure is available in the online journal.)

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7 See http://www.astronomy.villanova.edu/WDCatalog/index.html.
here (see below) follow this sequence at the red end, and broaden it at the blue end.

Our criteria initially resulted in the selection of 28 WDs from the MS99 sample. Seven of these were excluded because they are known WDs with circumstellar dust disks: WD 0408–041 (Kilic et al. 2006), WD 0843+516 (Gänsicke et al. 2012), WD 1015+161 (Jura et al. 2007a), WD 1116+026 (Jura et al. 2007a), WD 1150–153 (Kilic & Redfield 2007), WD 1541+650 (Kilic et al. 2012), and WD 1729+371 (Becklin et al. 2005; Kilic et al. 2005). Five WDs were excluded for being known central stars of planetary nebulae (CSPNs): WD 0558–756 (Henize & Fairall 1981; Rauch & Werner 1993), WD 0950+139 (Liebert et al. 1989), WD 1821+643 (Starrfield et al. 1985), WD 1958+015 (Napiwotzki & Schoenberner 1995), and WD 2333+301 (Schoenberner & Napiwotzki 1990). Another six were rejected for various reasons related to contamination of their photometry.

1. WD 0457–103 is in a known spectroscopic binary with a bright G–K star (63 Eri; Shara et al. 1997; Barstow et al. 1994); it remains unresolved despite a high resolution Hubble Space Telescope imaging investigation (Barstow et al. 2001).

2. WD 0725+318 has a nearby source (R.A. = 07:28:11.65, decl. = +31:43:46.57, J2000), which is revealed in the SDSS images of the field as a red background galaxy that is very bright in the IR and likely contaminates the WD photometry in both 2MASS and WISE.

3. WD 1109–225 is in a known unresolved spectroscopic binary with a bright A star (β Crt; Fleming et al. 1991).

4. WD 1201+437 is classified as a DC+dMe binary by Fleming et al. (1995). Xu et al. (1999) classify it as a quasar based on its X-ray properties; however, we note that their X-ray error circle has a 9″ radius, so this could be a misidentification. In either case, we would remove it from our sample.

5. WD 1235+321 has a stellar profile in the WISE images that is faint and extended, while the SDSS images show two nearby faint point sources that are likely contaminating the WISE photometry. These sources are a star located 5.6 west with \( i = 20.11 \) mag and \( z = 19.94 \) mag, and a galaxy located 6.2 east with \( i = 19.87 \) mag and \( z = 19.64 \) mag. There are three additional faint sources within 13″ of the WD (two to the south, one to the southwest in the direction of the bright star located 25″ southwest of the WD), all with \( i > 21 \) mag and \( z > 22 \) mag.

6. WD 1859+429 is in a wide binary with a common proper motion companion located \( \approx 15″ \) to the northeast. The common proper motion companion is not problematic; however, due to its proper motion, the WD is superposed on a field star in the 2MASS images. It is likely that this star contaminates the WISE photometry.

This leaves 10 WDs that we classified as targets-of-interest and for which we constructed UV–IR spectral energy distributions (SEDs). In addition to the 2MASS (Skrutskie et al. 2006) All Sky Data Release Point Source Catalog and WISE All Sky Release photometry, we utilized photometric data from the Galaxy Evolution Explorer (GALEX; Martin et al. 2005), the SDSS (Data Release 7; Abazajian et al. 2009), the AAVSO Photometric All Sky Survey (APASS Data Release 6), and the Spitzer Space Telescope Enhanced Imaging Products Source List (Cryogenic Release v2.0, 2013 January). For the purpose of modeling the SEDs, we converted the various photometric measurements from magnitudes into flux densities using published zero points for each photometric band (Bessell 1979; Skrutskie et al. 2006; Abazajian et al. 2009; Wright et al. 2010). All of the photometric data for the targets-of-interest plus the CSPNs and known WDs with dust disks, along with published spectral types, effective temperatures, and surface gravities of the WDs, are listed in Tables 1–3.

We then fit either a DA or DB model, as appropriate for the published WISE type, to the UV–optical–near-IR (JHK) portion of the target SEDs, using grids of H- and He-rich WD cooling models (kindly provided by P. Bergeron) that include the GALEX, SDSS, Johnson UBVI, 2MASS, and WISE bands (Bergeron et al. 1995; Holberg & Bergeron 2006). The published WD temperature and log \( g \) values from Table 1 were used as initial values (a “typical” value of \( \log g = 8.0 \) was assumed in cases for which there is no published value). We searched for best-fitting models within the 1σ uncertainties of the literature values of \( T_\text{eff} \) and log \( g \). For WDs with no published uncertainty for \( T_\text{eff} \), we assumed \( \pm 2000 \) K.

Seven of the targets have an obvious excess over the WD model in the IR. For these objects, we re-fit the entire SED using an additional circumstellar dust disk component. The model dust disk SED was calculated as originally devised by Jura (2003), following the procedure described in Debes et al. (2011b), with free parameters of the inner radius, width, and inclination. The minimum allowed inner disk radius was given by a conservative sublimation temperature of \( T_\text{subl} = 2100 \) K; in the case of our hottest WD (WD 0420+520, \( T_\text{eff} = 24300 \) K), we relaxed this criterion to \( T_\text{subl} = 2500 \) K in order to obtain the best dust disk model fit.

As noted above, the broad 10 μm silicate emission feature that is commonly seen in the IR spectra of WDs with circumstellar dust (Jura et al. 2009) could contribute in the W3 band; consequently, we did not use the W3 photometry to constrain the models. Any model that is too faint at W3 indicates the presence of a silicate emission feature or a significant amount of cool dust at large distances from the WD. If the model is too bright at W3, then this likely indicates that the assumed outer radius of the disk is too large. The silicate emission feature at 18–20 μm (e.g., seen in the IR spectrum of the archetype dusty WD G29–38 = WD 2326+049; Reach et al. 2009) is generally weaker in amplitude but broader than the 10 μm feature (Papoular & Pegourie 1983; Thompson et al. 2003; Jura et al. 2007b), and could contribute in the W4 band. The disk inclinations are generally poorly constrained by the models. The SEDs and model fits are shown in Figure 2; the WD and dust disk model parameters are listed in Table 4. These seven objects are our new candidate WDs with dust disks.

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8 See the explanatory supplement at http://wise2.ipac.caltech.edu/docs/release/allsky/expsup/
9 See http://www.aavso.org/apass.
### Table 1
System Parameters and Photometry (UV, Near-IR) of Selected MS99 White Dwarfs

| WD       | WISE Designation | Type | $T_{\text{eff}}$ (K) | log $g$ | Refs | fev (mag) | nUV (mag) | 2MASS J (mag) | H (mag) | Ks (mag) |
|----------|------------------|------|----------------------|--------|------|-----------|------------|--------------|---------|---------|
|          |                  |      |                      |        |      | (μJy)     | (μJy)      | (1.253 μm)   | (1.662 μm) | (2.159 μm) |
| 0249−052 | J025215.53−050231.3 | DB   | 17700 ± 548          | 8.16 ± 0.09 | 1 | 16.057 ± 0.033 | 15.682 ± 0.016 | 16.256 ± 0.116 | > 16.249 | > 15.735 |
| 0420−731 | J041937.81−730344.3 | DA   | ...                  | ...  | 2 | 14.955 ± 0.019 | 15.212 ± 0.015 | 16.217 ± 0.099 | 15.954 ± 0.179 | > 16.646 |
| 0420+520 | J042415.70+521010.6 | DA   | 20642 ± 3921         | 8.1   | 3 | 3783 ± 67 | 2987 ± 40 | 520 ± 129 | 425 ± 78 | < 146 |
| 0836+404 | J084007.64+401503.6 | DA   | 11870 ± 180          | 8.10 ± 0.05 | 4 | 17.254 ± 0.048 | 16.219 ± 0.020 | 15.840 ± 0.073 | 15.693 ± 0.130 | 15.845 ± 0.019 |
| 1046−017 | J104832.65−020112.3 | DB(Z) | 14620 ± 354          | 8.14 ± 0.13 | 1 | 16.651 ± 0.039 | 15.819 ± 0.009 | 16.030 ± 0.089 | > 15.481 | > 15.240 |
| 1448+411 | J145006.54+055337.7 | DA   | ...                  | ...  | 2 | 16.221 ± 0.031 | 16.143 ± 0.019 | 16.333 ± 0.111 | > 16.092 | > 16.271 |
| 2329+407 | J233135.90+410129.6 | DA   | 15900                | 7.91  | 5  | 13.933 ± 0.008 | 14.167 ± 0.006 | 14.213 ± 0.031 | 14.322 ± 0.058 | 14.249 ± 0.070 |

Notes. Upper limits are 2σ (95% confidence) levels.

*From MS99 and MSOonline.

References. (1) Bergeron et al. 2011; (2) no published $T_{\text{eff}}$ or log $g$ values; (3) Sion et al. 1988b; (4) Linoges & Bergeron 2010; (5) Holberg & Bergeron 2006; (6) Bergeron et al. 1997; (7) Koester et al. 2009; (8) Liebert et al. 2005; (9) Zuckerman et al. 2007; (10) Rauch et al. 1994; (11) Gianninas et al. 2010; (12) Bradley 2000; (13) Rauch & Werner 1995; (14) Kwitter & Jacoby 1989; (15) Chu et al. 2009; (16) Napiwotzki 1993.
| WD | u (μJy) | g (μJy) | r (μJy) | i (μJy) | z (μJy) | V (μJy) | g (μJy) | r (μJy) | i (μJy) |
|----|---------|---------|---------|---------|---------|--------|---------|---------|---------|
|     | (0.354 μ) | (0.477 μ) | (0.623 μ) | (0.762 μ) | (0.913 μ) | (0.44 μ) | (0.55 μ) | (0.477 μ) | (0.623 μ) |
| 0249-052 |          |          |          |          |          |        |          |          |          |
| 0420-731 |          |          |          |          |          |        |          |          |          |
| 0420+520 |          |          |          |          |          |        |          |          |          |
| 0836+404 |          |          |          |          |          |        |          |          |          |
| 1046-017 |          |          |          |          |          |        |          |          |          |
| 1448+411 |          |          |          |          |          |        |          |          |          |
| 2329+407 |          |          |          |          |          |        |          |          |          |
| 1146-290 |          |          |          |          |          |        |          |          |          |
| 1330+473 |          |          |          |          |          |        |          |          |          |
| 2152-548 |          |          |          |          |          |        |          |          |          |
| 0408-041 |          |          |          |          |          |        |          |          |          |
| 0843+516 |          |          |          |          |          |        |          |          |          |
| 1015+161 |          |          |          |          |          |        |          |          |          |
| 1116+026 |          |          |          |          |          |        |          |          |          |
| 1150-153 |          |          |          |          |          |        |          |          |          |
| 1541+650 |          |          |          |          |          |        |          |          |          |
| 1729+371 |          |          |          |          |          |        |          |          |          |
| EXCLUDED—Known WDs with Dust Disks |          |          |          |          |          |        |          |          |          |
| 0558-756 |          |          |          |          |          |        |          |          |          |
| 0950+139 |          |          |          |          |          |        |          |          |          |
| 1821+643 |          |          |          |          |          |        |          |          |          |
| 1958+015 |          |          |          |          |          |        |          |          |          |
| 2333+301 |          |          |          |          |          |        |          |          |          |

**Table 2**

Optical Photometry of Selected MS99 White Dwarfs

**Notes.** Upper limits are 2σ (95% confidence) levels.

a WD 1146-290 is too faint for detection by APASS; the tabulated BV photometry is from Bergeron et al. (1997).
### Table 3
Mid-infrared Photometry of Selected MS99 White Dwarfs

| WD         | W1 (mag) | W2 (mag) | W3 (mag) | W4 (mag) | IRAC-1 (mag) | IRAC-2 (mag) | IRAC-3 (mag) | IRAC-4 (mag) | MIPS-1 (mag) |
|------------|----------|----------|----------|----------|--------------|--------------|--------------|--------------|--------------|
|            | (μJy)    | (μJy)    | (μJy)    | (μJy)    | (μJy)        | (μJy)        | (μJy)        | (μJy)        | (μJy)        |
|            | (3.35 μm) | (4.60 μm) | (11.56 μm) | (22.24 μm) | (3.55 μm) | (4.495 μm) | (5.731 μm) | (7.872 μm) | (23.68 μm) |
| New WD Dust Candidate                      |          |          |          |          |               |               |               |               |               |
| 0249−052   | 16.468 ± 0.078 | 15.732 ± 0.149 | >12.819 | >8.981 |               |               |               |               |               |
| 0420−731   | 14.631 ± 0.029 | 13.974 ± 0.033 | 11.700 ± 0.112b | 9.718 ± 0.517b |               |               |               |               |               |
| 0420+520   | 14.653 ± 0.039 | 14.265 ± 0.060 | 11.492 ± 0.163b | 8.392 ± 0.235b |               |               |               |               |               |
| 0836+404   | 15.700 ± 0.057 | 15.245 ± 0.115 | >12.776 | >8.991 |               |               |               |               |               |
| 1046−017   | 15.836 ± 0.070 | 15.402 ± 0.123 | >12.208 | >8.753 |               |               |               |               |               |
| 1448+411   | 15.890 ± 0.044 | 15.497 ± 0.082 | 12.740 ± 0.309 | 9.527 |               |               |               |               |               |
| 2329+407   | 13.757 ± 0.027 | 12.956 ± 0.027 | 11.520 ± 0.184 | 9.184 |               |               |               |               |               |
| 1146−290   | 15.640 ± 0.054 | 15.327 ± 0.121 | >12.474 | >9.154 |               |               |               |               |               |
| 1330+473   | 16.011 ± 0.058 | 15.660 ± 0.122 | >13.071 | >9.330 |               |               |               |               |               |
| 2152−548   | 15.555 ± 0.057 | 15.249 ± 0.121 | >11.990 | >9.075 |               |               |               |               |               |
| Other Selected WDs                      |          |          |          |          |               |               |               |               |               |
| 0408−041   | 13.889 ± 0.028 | 13.022 ± 0.030 | 11.565 ± 0.183 | >9.207 |               |               |               |               |               |
| 0843+516   | 15.898 ± 0.061 | 15.301 ± 0.108 | >12.159 | >8.815 |               |               |               |               |               |
| 1015+161   | 15.521 ± 0.048 | 14.989 ± 0.083 | >12.252 | 9.046 ± 0.438 |               |               |               |               |               |
| 1116+026   | 14.215 ± 0.031 | 13.788 ± 0.046 | 12.417 ± 0.541 | 8.827 |               |               |               |               |               |
| 1150−153   | 14.681 ± 0.036 | 13.736 ± 0.044 | 12.128 ± 0.386 | 8.645 |               |               |               |               |               |
| 1541+650   | 14.638 ± 0.027 | 13.803 ± 0.030 | 12.928 ± 0.306 | 9.374 |               |               |               |               |               |
| 1729+371   | 14.965 ± 0.034 | 14.144 ± 0.042 | 11.703 ± 0.140 | 8.995 |               |               |               |               |               |
| 0558−756   | 16.877 ± 0.137 | 14.677 ± 0.052 | 10.394 ± 0.046 | 5.312 ± 0.030 |               |               |               |               |               |
| 0950+139   | 14.561 ± 0.037 | 13.543 ± 0.042 | 9.566 ± 0.042 | 7.327 ± 0.131 |               |               |               |               |               |
| 1821+643   | 16.098 ± 0.034 | 15.216 ± 0.041 | 10.933 ± 0.035 | 6.395 ± 0.036 |               |               |               |               |               |
| 1958+015   | 13.758 ± 0.046 | 12.360 ± 0.030 | 7.621 ± 0.016 | 2.684 ± 0.014 |               |               |               |               |               |
| 2333+301   | 16.732 ± 0.105 | 15.587 ± 0.127 | 11.740 ± 0.171 | 8.130 ± 0.183 |               |               |               |               |               |
| 63 ± 6     | 100 ± 3 | 638 ± 109 | 1146 ± 109 | 4681 ± 362 |               |               |               |               |               |

**Notes.** Upper limits are 2σ (95% confidence) levels. The Spitzer flux density uncertainties do not include systematic error terms, which amount to an additional ≈4.5% for IRAC and ≈6.5% for MIPS. 

* Spitzer Enhanced Imaging Products Source List (Cryogenic Release v2.0, 2013 January) data types for the IRAC-1–4 and MIPS-1 bands, respectively, as follows: 0, no data available; 1, flux density measurement (3/8's diameter aperture for IRAC, PSF-fit for MIPS); 2, bandfill measurement (i.e., no source detection with S/N > 3, so best combined position from detected bands is used to make a flux density measurement); 3, 3σ upper limit (not used here); 4, extended source, no photometry.

* These values should be treated as upper limits—see text for details.
Figure 2. Spectral energy distributions of the seven new WD with dust disk candidates. Photometric values are shown as filled circles; cataloged 2σ (95% confidence) upper limits for non-detections are shown as downward arrows. The unfilled circles are W3 and W4 photometry that is of questionable quality and should be treated as upper limits (see Sections 2.1.2 and 2.1.3). The wavelengths of the various photometric bands are indicated at the top of the figure (see Tables 1–3 for the wavelength of each band). The dashed line is a WD model fit, while the solid line is a combined WD + dust disk model (see Table 4 for disk parameters). The two models are generally indistinguishable shortward of ≈2 μm.

There are three reduced chi-squared ($\tilde{\chi}^2$) values listed in Table 4 for each model. These provide different measurements of the goodness of the model fit.

1. The parameter $\tilde{\chi}^2_{wd}$ refers to the goodness of just the WD model component compared to only the UV–optical–near-IR ($JHK$) data. In this wavelength region, we expect generally good agreement with a “naked” WD model even in the presence of circumstellar dust (which contributes most strongly at mid-IR and longer wavelengths). Large values of this statistic likely indicate deviations from the WD model in the UV; the GALEX data are typically among the brightest points in the SED and have very small relative errors. If $\tilde{\chi}^2_{wd}$ is large because of deviations in the UV, then the values of the other two $\tilde{\chi}^2$ statistics will also be large, as the errors are dominated by the poor fit in the UV. For example, removing the two UV points from the WD 2329+407 SED reduces $\tilde{\chi}^2_{wd}$ from 107 to 2.1 and $\tilde{\chi}^2_{disk}$ (see below) from 94 to 2.6. In the case of WD 1046−017, removing the UV points causes all of its $\tilde{\chi}^2$ values to drop to ≈1.4.

2. The parameter $\tilde{\chi}^2_{all}$ refers to the goodness of just the WD model component compared to all of the available photometric data. Large values (e.g., $\tilde{\chi}^2_{all} > \tilde{\chi}^2_{wd}$) indicate the need for an additional model component in the IR.

3. The parameter $\tilde{\chi}^2_{disk}$ refers to the goodness of the WD + dust disk model compared to all of the available photometric data. If $\tilde{\chi}^2_{disk} < \tilde{\chi}^2_{all}$, then the model was improved by the addition of a dust disk component. As noted above,
Figure 3. As in Figure 2, but for the three WDs selected by our target criteria that are not dust disk candidates.

Table 4

| WD        | Other Name | $T_{\text{eff,wd}}$ (K) | Distance (pc) | $R_{\text{in, disk}}$ ($R_{\text{wd}}$) | $R_{\text{out, disk}}$ ($R_{\text{wd}}$) | Inclination (°) | $\tilde{\chi}^2_{\text{wd}}$ | $\tilde{\chi}^2_{\text{all}}$ | $\tilde{\chi}^2_{\text{disk}}$ |
|-----------|------------|--------------------------|---------------|----------------------------------------|----------------------------------------|-----------------|-------------------------------|-------------------------------|-------------------------------|
| 0249−052  | HE 0245−0514 | 17823                    | 104           | 30                                      | 52                                      | 80              | 1.3                           | 5.1                           | 1.9                           |
| 0420−731  |            | 17653                    | 79            | 18                                      | 88                                      | 71              | 2.8                           | 151                           | 6.1d                          |
| 0420+520  | KPD 0420+5203 | 24301                   | 76            | 12∗                                      | 28                                      | 71              | 1.4                           | 64                           | 7.8d                          |
| 0836+404  | DF Lyn     | 11712                    | 59            | 16                                      | 86                                      | 89              | 1.0                           | 2.7                           | 1.2                           |
| 1046−017  | GD 124     | 14266                    | 75            | 28                                      | 38                                      | 80              | 17.6e                         | 18.0e                         | 17.7e                         |
| 1448+411  | CBS 204    | 13571                    | 80            | 26                                      | 36                                      | 80              | 0.3                           | 9.5                           | 0.9d                          |
| 2329+407  | EGG 160    | 13900                    | 33            | 28                                      | 68                                      | 80              | 107e                          | 155e                          | 94e                          |
| 1146−290  | Ruiz 440−146 | 5000                      | 26            | ...                                      | ...                                      | ...             | 12                            | 32                            | ...                           |
| 1330+473  | PG         | 21223                   | 91           | ...                                      | ...                                      | ...             | 461                           | 384                           | ...                           |
| 2152−548  | IES 2152−54.8 | 45050                  | 123           | ...                                      | ...                                      | ...             | 0.7                           | 10                            | ...                           |

Notes.

∗ Dust located at $R_{\text{in, disk}}$ is at the assumed sublimation temperature.

† $\tilde{\chi}^2_{\text{wd}}$ value of the WD model fit compared to only the GALEX UV, optical, and 2MASS near-IR data points.

‡ $\tilde{\chi}^2$ value of the WD model fit compared to all available data points.

§ $\tilde{\chi}^2_{\text{all}}$ value of the WD + dust disk model fit compared to all available data points.

d These values are large due to the inclusion of bright W3 and/or W4 points—see discussion in the text.

e Large $\tilde{\chi}^2$ values due to poor fit in the UV—see discussion in the text.

Three targets-of-interest selected by our criteria (WD 1146−290, WD 1330+473, and WD 2152−548) show no strong IR excess (see Figure 3), and they are among the selected WDs with (W1−W2) color closest to the +0.3 mag criterion (see Figure 1). The first of these is a very cool WD (see Table 1 and notes below). It has a distinctive SED shape compared to the others in our selected sample, and its selection by our criteria was likely a by-product of its very low temperature. The latter two WDs have only very slightly elevated W2 flux densities compared to the WD model. In particular, only the W2 point in WD 2152−548 is elevated compared to the model; the adjacent IRAC-2 point (as well as the other IRAC data) agrees with the model. Thus, the W2 value for WD 2152−548 should be treated with caution. If real, then the IR excesses in WD 1330+473 and WD 2152−548 are very weak and could indicate that only a small amount of cool dust is present. This situation presents similarities to the weak IR excesses found in PG 1457−086 (Farihi et al. 2009) and HE 0106−3253 (Farihi et al. 2010b), which are inferred to be due to narrow circumstellar rings of dust instead of full disks, as well as to the several known WDs with combined gas and dust disks (e.g., Gänsideke et al. 2006; Brinkworth et al. 2009, 2012). The presence of co-mingled gas and dust disks could indicate that a significant amount of dust has
been converted to gas through either sublimation (Melis et al. 2010) or collisions (with itself or possibly with pre-existing circumstellar material; Jura 2008; Girven et al. 2012).

2.1. Notes on Individual Targets

We have examined the publication record for each of the 10 targets-of-interest, and briefly describe any relevant features below. We also vetted the WISE data for each of these sources for evidence of red contaminating sources in the photometry aperture (as described in Debes et al. 2011b); relevant notes are included below.

2.1.1. WD 0249−052

Voss et al. (2007) and Limoges & Bergeron (2010) do not note any atmospheric contamination (including hydrogen) in this DB WD. In the former study, hydrogen was assumed to be absent unless a visual inspection of the optical spectrum revealed H lines (corresponding to a detection limit of Hα equivalent width $>300$ mÅ). In the latter study, it appears that hydrogen was only utilized in the model spectrum analysis if the WD had been previously identified as a hydrogen-rich helium (DBA) WD. Additional examination of the two (somewhat noisy) spectra of this WD from the Voss et al. (2007) study yields no obvious metal lines, and limits of [Ca/He] $< -8.0$ and [Mg/He] $< -6.7$ (D. Koester 2013, private communication). On the other hand, Bergeron et al. (2011) find [H/He] = −5.47(59) (but no metals) by utilizing high S/N spectra of the Hα region. None of these three analyses, however, conclude that metal contamination (signified by the presence of Ca absorption in the optical spectrum) is present. We have no concerns about the quality of the WISE photometry.

2.1.2. WD 0420−731

There is no detailed information on this WD in the literature. However, there is a source (WISE-J041933.70−730333.9) located $\approx 22''$ northwest of the WD, which is faint in W1 and W2, but becomes much brighter in the W3 and W4 bands (slightly brighter than the WD). This source separation is well beyond the $1.3 \times$ (FWHM$_{W1}$) $\approx 7.8$ radius, interior to which contamination of the WISE All Sky Catalog photometry can occur (see discussion in Debes et al. 2011b); nonetheless, we tested for contamination from the neighboring source. To do so, we used the IRAF$^{13}$ implementation of DAOPHOT (Stetson 1987) to obtain PSF-fit photometry for the WD and the nearby source in the W3 Atlas images, using the nearby bright star WISE-J041948.50−730317.2 as a PSF template and magnitude calibrator. We obtain $W3_{psf} = 11.69(40)$ mag for the WD and $W3_{psf} = 11.60(33)$ mag for the nearby source, in agreement with the WISE catalog values of $W3 = 11.700(112)$ mag and $W3 = 11.642(106)$ mag, respectively. Nonetheless, the local background is patchy and bright in W3 and W4, so it is prudent to treat the W3 and W4 photometry as upper limits until higher resolution imaging data are available.

2.1.3. WD 0420+520

There is no detailed information on this WD in the literature. The cataloged W3 and W4 flux densities for this target are quite bright, and there is no obvious point source at the position of the WD in the WISE W3 and W4 Atlas images. Thus, these values should be treated as upper limits.

2.1.4. WD 0836+404

This is a ZZ Ceti-type pulsating WD (Vauclair et al. 1997). Farihi et al. (2005) found no evidence for a low luminosity companion from a survey utilizing proper motion measurements, deep imaging, and near-IR photometry. A limit on atmospheric metal contamination was set by Zuckerman et al. (2003), at $[\text{Ca}/\text{H}] < -7.72$. There is a bright ($V = 10.9$ mag) star (2MASS J08401164+4015211) located $\approx 43''$ east of the WD. While this star is far enough from the WD to not pose a contamination risk for the WISE photometry, we note that a diffraction spike from the star passes near the WD in the WISE Atlas images. Contamination warnings due to diffraction spikes are included in the WISE All Sky Catalog; such a warning was not flagged for WD 0836+404. Nonetheless, to confirm this we performed DAOPHOT PSF-subtraction photometry on the W2 Atlas image, as described above. We used the nearby stars WISE-J084000.92+401704.4 and WISE-J084022.86+401250.6 to construct a PSF template, and the mean photometry of the PSF stars plus several nearby stars (WISE-J083954.52+401509.5, WISE-J084001.71+401415.7, and WISE-J084022.35+401424.8) that are comparable in brightness to the WD as a magnitude calibrator. We obtain $W2_{psf} = 15.29(51)$ mag for the WD, in agreement with its WISE catalog value of $W2 = 15.245(115)$ mag. The nominal W2 PSF photometry for all 6 of the tested stars (including the WD) agrees to better than 1% with the WISE catalog values. So, we consider it unlikely that the nearby diffraction spike has contaminated the WISE photometry of the WD.

2.1.5. WD 1046−017

This is a known DB WD and there is tentative evidence that it might be metal-rich: Sion et al. (1988a) noted a possible weak Ca I K feature in its optical spectrum (equivalent width $< 10$ mÅ), while Zuckerman et al. (2010), Bergeron et al. (2011), and Jura & Xu (2012) set limits of $[\text{Ca}/\text{H}] < -10.9$ (Ca I equivalent width $\leq 5$ mÅ), $[\text{H}/\text{He}] \lesssim -6.5$, and $\log(dM_{\text{metal}}/dt)$ (g s$^{-1}$) $< 6.20$. Thus, the metal-rich status of this WD remains uncertain (but unlikely). Farihi et al. (2005) found no evidence for a low luminosity companion from a survey utilizing proper motion measurements, deep imaging, and near-IR photometry. We have no concerns about the quality of the WISE photometry.

2.1.6. WD 1146−290

The equivalent width of Hα in this DA WD is 5.9 Å (Bergeron et al. 1997). There is no other detailed information on this WD in the literature. We have no concerns about the quality of the WISE photometry.

2.1.7. WD 1330+473

No IR excess or evidence for a dust disk is noted in the near- and mid-IR photometric and spectroscopic survey of Barber et al. (2012). Farihi et al. (2005) found no evidence for a low luminosity companion. We have no concerns about the quality of the WISE photometry.

2.1.8. WD 1448+411

There is no detailed information on this WD in the literature. We have no concerns about the quality of the WISE photometry.

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$^{13}$ IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
Thus, there appears to be no overt reason to be concerned about agreement with the catalog photometry of W1 (Figure 4), and we obtain W1 psf ≈ 13.75(5) mag, which is in agreement with the catalog photometry of W1 = 13.757(27) mag. Thus, there appears to be no overt reason to be concerned about the WISE photometry of WD 2329+407.

3. DISCUSSION AND CONCLUSIONS

Many of the “original” WDs with dust disks that were discovered before 2011 have IR excesses that are detectable in the near-IR (JHK) bands. In all but one (WD 0420+520) of the new dust disk candidates presented here, the excess emission due to dust is only apparent at wavelengths ≥3 μm. It is possible that the current census of WDs with dust disks that produce an excess detectable at K-band and shorter wavelengths (e.g., using 2MASS or UKIDSS data; see Wachter et al. 2003; Wellhouse et al. 2005; Hoard et al. 2007; Steele et al. 2011) is close to complete for the entire sample of known WDs (at least to the detection limits of existing near-IR all-sky surveys). The WD dust disk candidates now being found using longer wavelength data from WISE and Spitzer are drawn from a previously underrepresented region of parameter space, in which the dust disks are overall cooler, narrower in radial extent, and/or contain fewer emitting grains.

In Figure 5, we have plotted the dust disk inner edge radius as a function of WD effective temperature for the seven new candidates from this paper, the candidates in Debes et al. (2011b), and various published dust disk models for other WDs (see Table 5). There is a direct relationship between the WD temperature and the temperature of dust at a given radius (Jura 2003),

$$T_{\text{dust}}(R) \propto R^{-3/4} T_{\text{wd}}. \quad (1)$$

which is used to plot isothermal contours in Figure 5 for the model dust disks. For an assumed dust sublimation temperature, the corresponding contour shows the minimum inner radius of the disk as a function of WD temperature; in general, the contours illustrate the temperature at a given radius in the disk for a given WD temperature. A typical boundary condition of WD dust disk models is that no dust is allowed to be hotter than the assumed sublimation temperature; in other words, dust is not allowed at radii closer to the WD than the radius at which the sublimation temperature (according to Equation (1)) is reached. In many cases, the hottest dust in the disk models is at the assumed sublimation temperature (disk models with inner edges at the assumed sublimation temperature are indicated in Tables 4 and 5). Such a disk extends inward toward the WD as far as possible—its inner edge lies at the sublimation radius around the WD, so dust cannot survive any closer to the WD. On the other hand, disks that have inner edge radii corresponding to temperatures below the dust sublimation temperature could, in principle, extend inward closer to the WD but do not. In such cases, possible reasons for the lack of dust grains close to the WD include (but are not limited to):

1. Grains close to the WD might have been depleted due to a higher rate of collisions with other grains. This might have occurred in the handful of known WDs with gas+dust disks, in which the gas and dust share spatially overlapping, but not identical, radial distributions, implying that dust sublimation alone cannot account for the presence of gas/lack of close-in dust (e.g., Brinkworth et al. 2012). Additionally, objects like WD 1456+298 (G166−158) have a very weak IR excess corresponding to the presence of only cool dust (see additional discussion of this object below).

2. A spinning WD with a strong magnetic field might sweep up paramagnetic or diamagnetic dust grains interior to a critical radius. A similar process operates in the intermediate polar class of cataclysmic variable to produce a truncated gaseous accretion disk around the WD (see review of this class in Warner 2003). Based on observations of the Ca II lines during pulsations of the archetype dusty WD G29−38, Thompson et al. (2010) have suggested that the Ca is being accreted onto the poles of the WD, rather than equatorially,
suggesting that the WD is magnetic. Brinkworth et al. (2007, see the Appendix in that paper) calculated the critical surface charge on a dust grain, $Q_{\text{crit}}$, such that the motion of the dust would be influenced by the WD magnetic field. They found that $Q_{\text{crit}}$ for dust grains at the sublimation radius around a 14,200 K WD with a field strength of $B \approx 25$ MG is more than an order of magnitude larger than the likely surface charge of the grains based on observations of in situ interplanetary dust grains in the Solar System. However, they note that the value of $Q_{\text{crit}}$ is several orders of magnitude smaller than the value of $Q_{\text{max}}$, at which the electrostatic tensile stress in the dust grain interiors would be sufficient to fracture (i.e., destroy) the grains. In addition, $Q_{\text{crit}} \propto R^{3/2} B^{-1}$ (where $R$ is the distance from the center of the WD to the dust grain), leaving open the possibility that magnetic interactions could be effective around WDs with larger magnetic fields and/or cooler temperatures (allowing the dust to approach closer to the WD before sublimating). Finally, Brinkworth et al. (2007) did not consider any intrinsic para- or diamagnetic properties of the dust itself, which could enhance interaction with the WD magnetic field. Other than these two examples (one observational, one theoretical), there has been (to our knowledge) little exploration of this possibility.

There is, of course, some ambiguity in the interpretation of Figure 5. A given disk could appear to not reach the sublimation radius if the assumed sublimation temperature was higher than the true sublimation temperature for the particular species of dust in the observed disk. In the bulk of cases, however, the published models of dust disks extend inward to the sublimation radius even when the assumed sublimation temperature is quite high (e.g., a majority of the large sample in Debes et al. 2011b with $T_{\text{subl}} = 2100$ K, or WD 0420+520 in this work). Apparently, most of the currently known dusty WDs have “hot” disks in which the dust extends inward quite close to the WD, until it reaches the “sublimation barrier.” In contrast, five of the seven dust disk candidates presented here have maximum dust temperatures of $\lesssim 1000$ K, safely below reasonable lower limits of the sublimation temperature for metallic dust. They are, therefore, truly “cool” disks in which dust is depleted close to the WD and is mainly present substantially exterior to the sublimation radius. These disks are narrower in radial extent than an otherwise identical disk in which the inner edge extends all the way to the sublimation radius. The apparent bias toward sublimation-limited disks does not, however, imply that “hot” WD dust disks are necessarily more intrinsically common than “cool” disks. The “hot” disks are easier to find, since they produce strong IR excesses that can be detected in the near-IR.

Three of our dust disk candidates (WD 0249–052, WD 0836+404, WD 1046–017) have optical spectroscopic studies noting the absence of atmospheric metal pollution. One would expect to find metals in the atmosphere of a WD with an IR excess indicating a dust disk, as some of the dust will accrete onto the star. The DB WDs (WD 0249–052, WD 1046–017) have gravitational settling times for metals in their helium-rich atmospheres that are much longer than for DA WDs; metals can persist for up to a Myr or longer after accretion ceases, making them appear as metal-rich WDs for a substantial time after the dust disk has dissipated (typical disk lifetimes are $\sim 0.03$–5 Myr; Girven et al. 2012). While there appear to be firm constraints on the lack of accreted metals in WD 0249–052 (see Section 2.1.1), the situation for WD 1046–017 is less certain (see Section 2.1.5). Possibly the most viable explanation for

![Figure 5](image-url)
The presence of a dust disk around a DB WD that is not metal-polluted is that the disk is newly formed and the abundance of accreted metals on the WD is not yet in a steady state and has not reached the threshold of detection.

On the other hand, because of the short settling times of DA WDs, essentially any process that causes the accretion of metals from the dust disk to be out of steady state could produce the phenomenon of a WD with an IR excess but no spectroscopic signature of metal pollution. In the case of the DA WD among these three, we note that the limit on the metal contamination of WD 0836+404 is not very stringent.

### Table 5
Published WD Dust Disk Model Parameters

| WD       | Other Name | Type | \(T_{\text{eff}, wd}\) (K) | \(R_{\text{in}, disk}\) \((R_{wd})\) | \(R_{\text{out}, disk}\) \((R_{\text{in}, disk})\) | Inclination (°) | \(T_{\text{subl}}\) (K) | Reference | Notes |
|----------|------------|------|-----------------|-----------------|-----------------|----------------|-----------------|-----------|-------|
| 0106−328 | HE 0106−3253 | DAZ   | 15700           | 15               | 21               | 81             | −               | Farihi et al. (2010b) | 1       |
| 0110−565 | HE 0110−5630 | DAZ   | 19200           | 90               | 25               | 58             | 1800            | Girven et al. (2012) | ...     |
| 0146+187 | GD 16       | DAZ   | 11500           | 12               | 30               | 48             | 1200            | Farihi et al. (2009) | ...     |
| 0300−013 | GD 40       | DBZ   | 15200           | 18               | 44               | 78             | 1200            | Jura et al. (2007a) | 2       |
| 0307+077 | HS 0307+0746 | DAZ   | 12250           | 13               | 35               | 81             | 1000−1500       | Jura et al. (2009) | 2       |
| 0408−041 | GD 56       | DAZ   | 14400           | 16               | 104              | 0              | 1200            | Jura et al. (2007a) | ...     |
| 0435+410 | WD 61       | DAZ   | 17280           | 19               | 26               | 79             | 1300            | Farihi et al. (2011) | ...     |
| J0738+1835 | SDSS J073842.56+183509.6 | DBZ   | 17500           | 17               | 36               | 85             | 1800            | Girven et al. (2012) | ...     |
| 0842+231 b | Ton 345     | DBZ   | 13600           | 9               | 25               | 58             | 1800            | Brinkworth et al. (2012) | ...     |
| 0843+516 | PG, SDSS J084702.28+512853.4 | DA   | 18600           | 13               | 187              | 83             | 1800            | Brinkworth et al. (2012) | ...     |
| J0959−0200 | SDSS J095904.69−020447.6 | DA   | 13280           | 10               | 25               | 0              | 1200            | Farihi et al. (2012) | ...     |
| 1015+161 | PG          | DAZ   | 19300           | 24               | 42               | 73             | 1200            | Jura et al. (2007a) | ...     |
| 1041+091 b | SDSS J104153.53+085558.2 | DAZ   | 18330           | 23               | 80               | 60             | 1200−1500       | Melis et al. (2010) | ...     |
| 1116+026 | GD 133      | DAZ   | 12200           | 18               | 38               | 85             | 1400            | Brinkworth et al. (2012) | ...     |
| 1150−153 | EC11507−1519 | DAVZ  | 12200           | 18               | 50               | 79             | 1000−1500       | Jura et al. (2009) | 2       |
| J1221+1245 | SDSS J122150.81+124513.3 | DAZ   | 12250           | 10               | 30               | 0              | 1000−1500       | Jura et al. (2009) | 2       |
| 1349−230 | HE 1349−2305 | DAVZ  | 17000           | 13               | 35               | 85             | 1800            | Girven et al. (2012) | ...     |
| 1456+298 | G166−58     | DAZ   | 7400            | 29               | ...              | ...            | 1200            | Farihi et al. (2008) | 3       |
| 1457−086 | PG          | DAZ   | 20400           | 19               | 21               | 73             | 1200            | Farihi et al. (2009) | ...     |
| 1541+650 | KX Dra       | DAV   | 11880           | 11               | 32               | 60             | ...             | Kilic et al. (2012) | ...     |
| J1557+0916 | SDSS J155720.77+091624.7 | DA   | 22810           | 25               | 52               | 60             | 1200            | Farihi et al. (2012) | ...     |
| J1617+1620 | SDSS J161717.04+162022.3 | WD   | 13432           | 9                | 20               | 70             | 1800            | Brinkworth et al. (2012) | ...     |
| J2209+1223 | SDSS J220934.84+122336.5 | DBZ   | 17300           | 15               | 45               | 57             | 1200            | Farihi et al. (2009) | ...     |
| 2221−165 | HE 2221−1630 | DAZ   | 10100           | 11               | 21               | 60             | ...             | Farihi et al. (2010b) | 1       |
| 2326+049 | G29−38      | DAZ   | 11600           | 12               | 22               | 45             | 2000            | von Hippel et al. (2007) | ...     |

**Notes.** This table does not include the 52 WD dust disk candidates from Debes et al. (2011b)—see their Table 7. (1) Published model radii given in units of \(R_{\odot}\); we have assumed \(R_{\text{in}, disk} = 0.013 R_{\odot}\). (2) \(R_{\text{out}, disk}\) is transition radius from optically thick to thin. (3) Possible double degenerate (WD+WD) binary with a circumbinary dust disk. (4) These two disk models have degenerate parameters and produce comparably good fits to the data.

* Dust located at \(R_{\text{in}, disk}\) is at the assumed sublimation temperature.
* WD types from MSonline or SIMBAD.
* WD has a gas+dust disk.
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