SPITZER OBSERVATIONS OF WHITE DWARFS: THE MISSING PLANETARY DEBRIS AROUND DZ STARS

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ABSTRACT

We report a Spitzer/Infrared Array Camera search for infrared excesses around white dwarfs, including 14 newly observed targets and 16 unpublished archived stars. We find a substantial infrared excess around two warm white dwarfs—J220934.84+122336.5 and WD 0843+516, the latter apparently being the hottest white dwarf known to display a close-in dust disk. Extending previous studies, we find that the fraction of white dwarfs with dust disks increases as the star’s temperature increases; for stars cooler than 10,000 K, even the most heavily polluted ones do not have ~1000 K dust. There is tentative evidence that the dust disk occurrence is correlated with the volatility of the accreted material. In the Appendix, we modify a previous analysis to clarify how Poynting–Robertson drag might play an important role in transferring materials from a dust disk into a white dwarf’s atmosphere.

Key words: circumstellar matter – minor planets, asteroids: general – white dwarfs

Online-only material: color figures

1. INTRODUCTION

White dwarfs are the final evolutionary stage of stars with masses less than about eight solar masses. The first infrared excess around a white dwarf was discovered more than 20 years ago (Zuckerman & Becklin 1987). Since 2005, primarily thanks to the Spitzer Space Telescope (Werner et al. 2004), progress has been dramatic. Including WD 0843+5161 and J220934.84+122336.5 (hereafter J2209+1223), which are reported in this paper, there are 24 confirmed white dwarfs with a warm disk and multiple additional candidates (see our Table 1, an extension of Table 1 in Farihi et al. 2009). Recently, observations from the Wide-field Infrared Survey Explorer (WISE) mission (Debes et al. 2011a, 2011b) and the UKIRT Infrared Deep Sky Survey (UKIDSS; Steele et al. 2011; Girven et al. 2011) are also contributing to the disk studies.

There are three classes of dust disks detected around a white dwarf: (1) ~100 K dust, which is found around ≥15% pre-white dwarfs and white dwarfs, sometimes in the center of planetary nebulae (Chu et al. 2011). The source of the dust is believed to be the collisions among analogs to Kuiper Belt objects in the system (Bonsor & Wyatt 2010; Dong et al. 2010). (2) ~500 K dust around two cool stars, G 166−58 (T_{\text{eff}} = 7400 K; Farihi et al. 2008b) and PG 1225−079 (T_{\text{eff}} = 10,500 K; Farihi et al. 2010b). A model that reproduces these data invokes emission from an opaque dust ring with a large, dust-free inner hole and an outer boundary within the tidal radius of the white dwarf. However, there are only two dust rings in this class and their origin is uncertain. (3) ~1000 K dust, which is found in the remaining 22 white dwarfs listed in Table 1. In these systems, all the dust lies within the star’s tidal radius and the inner boundary is determined by the location where the refractories rapidly sublimate. The 1000 K excess can be fit with a flat opaque dust disk (Jura 2003), which is substantial at wavelengths greater than 3 μm and can be easily studied with Warm Spitzer; we focus on discussing this class of disk in this paper.2

Gravitational settling of heavy elements is usually so effective in white dwarfs cooler than 25,000 K that their atmospheres are typically pure hydrogen or pure helium (Koester 2009). However, about 25% of DAs (white dwarfs with hydrogen-dominated atmosphere) and 33% of DBs (white dwarfs with helium-dominated atmosphere) have atmospheric pollution (Zuckerman et al. 2003, 2010). Given that the diffusion timescale of heavy elements is orders of magnitude less than a white dwarf’s cooling age (Koester 2009), it is unlikely that those heavy elements are intrinsic. Theoretical calculations show that tidal disruption and subsequent accretion of small bodies in the planetary system can explain the source of pollution in these objects (Debes & Sigurdsson 2002; Jura 2003; Bonsor et al. 2011). Kilic et al. (2006) first showed a correlation between the presence of an orbiting dust disk and a high level of heavy element pollution in the star’s photosphere. Subsequent observations have confirmed this trend and supported the small body accretion model (Jura et al. 2007; Farihi et al. 2008a, 2008b, 2009, 2010b). Thus, studying polluted white dwarfs provides invaluable measures of the bulk composition of extrasolar minor planets (see, for example, Klein et al. 2010).

However, as can be seen in our Table 1 and in Farihi et al. (2009), almost all the disk-host stars have effective temperatures of at least 9500 K. Here, we report the results from a Warm Spitzer Cycle 7 program, searching for infrared excesses around polluted cool white dwarfs and a few highly polluted warmer targets. Additionally, we reduced some unpublished archived Spitzer data.

Target selections and observations are presented in Section 2. In Section 3, we describe data reduction procedures and spectral energy distribution (SED) fits to the data. In Section 4, the main result is discussed: we continue to find dust disks around warm polluted white dwarfs but no dust around highly polluted cool stars. In Section 5, we explore the possible correlations between the presence of a dust disk and other characteristics of the star in addition to its temperature. Possible scenarios that can account for the presence of heavy elements without producing a dust disk are discussed in Section 6. Conclusions are presented in Section 7. In the Appendix, we assess the importance of Poynting–Robertson (P-R) drag on the entire dust disk as a mechanism to transfer material from the disk into the white dwarf’s atmosphere.

1 After reading a short description on http://www.arXiv.org of a survey on dust disks around white dwarfs (Chu et al. 2010), we learned from Y.-H. Chu that their team has independently found the infrared excess for this star.

2 In the following sections, unless specifically stated, dust disk and infrared excess all refer to this 1000 K dust.
Table 1
Warm Dust Disks and Candidates Discovered Since 2010

| WD     | Name           | SpT | $T_e$ (K) | $V$ (mag) | Discovery Year | Discovery Telescope | Ref. |
|--------|----------------|-----|------------|-----------|-----------------|---------------------|------|
| 0106–328 | HE 0106–3253  | DAZ | 15,700     | 16.50     | 2010           | Spitzer             | 1    |
| 0307+077 | HS 0307+0746  | DAZ | 10,200     | 16.40     | 2010           | Spitzer             | 1    |
| 0435+410 | GD 61      | DBZ | 17,280     | 14.80     | 2010           | Gemini/NIRI         | 3    |
| 0843+516 | PG 0843+517  | DA  | 23,900     | 16.15     | 2010           | UKIRT               | 7    |
| 1225–079 | PG 1225–079a | DZAB| 10,500     | 14.80     | 2010           | Spitzer             | 4    |
| 1541+650 | PG 1541+651  | DA  | 11,880     | 15.81     | 2011           | PARITEL/Spitzer     | 8    |
| 2221–165 | HE 2221–1630 | DAZ | 10,100     | 16.10     | 2010           | Spitzer             | 1    |

Notes. This table is supplementary to Table 1 in Farihi et al. (2009), which lists 14 white dwarfs with an infrared excess discovered at that time. GD 303, which might have a marginal excess at $2\sigma$ level at the IRAC 4 band (Farihi et al. 2010b), is excluded from this table. Debes et al. (2011b) have very recently reported multiple debris disk candidates from WISE data; they are not listed here.

*a This is SDSS r magnitude.
*b WD 1225–079 is reported in Farihi et al. (2010b) to have a 4$\sigma$ excess in the IRAC 7.9 $\mu$m band.
*c Melis et al. (2011) derived a stellar temperature of 23,470 K for this star.
*d These are debris disk candidates that need to be confirmed with more infrared data as the UKIRT observation only extends to the $K$ band.

References. (1) Farihi et al. 2010b; (2) Farihi et al. 2011; (3) Dufour et al. 2010; (4) This work; (5) Debes et al. 2011a; (6) Girven et al. 2011; (7) Steele et al. 2011; Kilic et al. 2012.

Table 2
Cycle 7 White Dwarf Targets

| WD     | Name | $T_e$ (K) | SDSS z (mag) | [Ca]/[He]$^a$ | Ref. |
|--------|------|-----------|--------------|----------------|------|
| 0033–114 | J003601.37–111213.8 | 7280         | 17.18        | −9.26          | 1    |
| 0216–095 | J021836.69–091944.8  | 9560         | 17.84        | −10.63         | 1    |
| 0936+560 | J093942.29+555048.7  | 8680         | 17.18        | −8.51          | 1    |
| 1035–003 | J103809.19–003222.5  | 8200         | 17.30        | −10.27         | 2    |
| 1212–023 | J121456.39–024028.4  | 6000         | 17.50        | …              | 3    |
| 1244+498 | J124703.28+493423.6  | 16,800       | 17.21        | …              | 4    |
| 113095+26+49359.7  | J113095.26+49359.7 | 8620         | 17.67        | −10.16         | 1    |
| G 199–63    | 8900       | 17.15        | −9.39        | 1    |
| LP 219–80   | 6770       | 16.91        | −11.35       | 1    |
| J220934.84+122336.5 | 17,300  | 17.91        | −6.16$^d$    | 4    |
| J222802.05+120733.3 | 6760      | 16.36        | −9.96        | 1    |
| 2222+683  | G 241–6    | 15,300       | 16.07        | −7.25          | 5    |

Notes. 
*a Abundances are expressed as $[X]/[Y] = \log [n(X)/n(Y)]$; where $n(X)$ is the number abundance.
*b This star is reported to be 11,500 K in Kilic et al. (2008).
*c This star is reported to be 6770 K and $[\text{Ca}]/[\text{He}] = −9.44$ in Dufour et al. (2007).
*d This value is derived from measuring the equivalent width of $\text{Ca}\,\lambda 3933.7$ Å from the SDSS spectra and extrapolating from GD 61, a heavily polluted white dwarf with similar effective temperature and surface gravity.

References. (1) Dufour et al. 2007; (2) Koester et al. 2011; (3) Reid et al. 2001; (4) Eisenstein et al. 2006; (5) Zuckerman et al. 2010.

2. OBSERVATIONS

2.1. Source Selection

The 14 targets of our Cycle 7 program are listed in Table 2. Ten stars are newly identified DZs with distinctively large amount of atmospheric calcium detected in the Sloan Digital Sky Survey (SDSS) spectrum; they all have $T_e < 10,000$ K and $m(z) < 18.0$ mag (0.23 mJy; Dufour et al. 2006, 2007). Four additional DBZs$^4$ with $T_e \sim 15,000$ K are also included: three stars from Eisenstein et al. (2006) plus G 241–6, which was recognized recently to be a near-twin of GD 40, a highly polluted white dwarf with a dust disk (Zuckerman et al. 2010; Klein et al. 2010).

$^3$ DZs are cool white dwarfs that display trace elements other than carbon; it is thought that DZs have a helium-dominated atmosphere, but the gas is too cool for the helium lines to be detected.

$^4$ DBZs are DBs with detected heavy elements in the atmosphere.
For the completeness of the sample, we also report Infrared Array Camera (IRAC) 3.6–7.9 μm fluxes for 16 single DA white dwarfs from the unpublished archived Cycle 3 program 30856. These stars all have well-determined temperatures, surface gravities, as well as highly accurate SDSS photometry, which is crucial in determining the presence of a disk. Relevant parameters are listed in Table 3.

### 2.2. Observing Strategies

*Spitzer* has been operated in the warm-phase mission since the depletion of cryogen in 2009 May. The two shortest wavelength channels (3.6 μm and 4.5 μm) of the IRAC (Fazio et al. 2004) continue to function and were used in this study to obtain broadband images. The observations were performed by using a 30 s frame time with 30 medium size dithers in the cycling pattern, resulting in a 900 s total exposure time in each IRAC channel.

The archived data were obtained between 2006 and 2007. The observing mode was random nine-point large dithering with a frame time of 30 s, resulting in a total of 270 s in each IRAC channel.

### 3. DATA ANALYSIS

#### 3.1. Data Reduction and SED Fits

Following the data reduction procedures described in Farihi et al. (2008a, 2008b, 2009), each exposure was processed with MOPEX (version 18.4.9) to create a single mosaic with a pixel size of 0.′6. Though the intrinsic plate scale is 1.′2 pixel−1, a 0.′6 pixel−1 mosaic was used because it has a better spatial resolution and the 3.6 μm and 4.5 μm images are oversampled. Aperture photometry was performed on the combined mosaic using both: (1) the standard IRAF *apphot* task and (2) the Astronomical Point-source EXtractor (APEX) in MOPEX. We tried an aperture size of both 2 (2.′4) and 3 (3.′6) native pixels with a sky annulus of an inner radius of 5 native pixels (6′0) and an outer radius of 15 native pixels (18′0). We found that in some cases even in a clean field, the measured flux in these two aperture sizes can differ up to 5% and we report the average flux weighted by their signal-to-noise ratio. To derive the aperture correction factor, we performed aperture photometry in the point response function (PRF) images in each band with our set of parameters. The PRF is the convolution of the point-spread function (PSF) of the telescope and the pixel response function of the detector and it is provided by the Spitzer Science Center. There are three factors contributing to the total uncertainty: 5% calibration uncertainty, which is based on previous studies of white dwarfs (Farhi et al. 2008a), rather than the 2%–3% value optimally derived for other targets (Reach et al. 2005; Bohlin et al. 2011), measurement error and uncertainties caused by the choice of aperture radius; these uncertainties were all added in quadrature. The fluxes independently obtained by IRAF and APEX agree to within 5%. To be conservative, we report the values that have the larger measurement error in Tables 4 and 5.

When there is a background source, proper motion analysis is performed to accurately determine the position of the target.

### References

1. Holberg & Bergeron 2006; 2. Koester et al. 2009; 3. Liebert et al. 2005.

### Table 3

| WD         | $T_{\text{eff}}$ (K) | SDSS $z$ (mag) | Ref. |
|------------|----------------------|----------------|------|
| 0816+297   | 16,700               | 16.53          | 1    |
| 0819+363   | 18,700               | 16.38          | 1    |
| 0843+516   | 23,900               | 16.86          | 1    |
| 0937+505   | 35,900               | 16.86          | 1    |
| 1017+125   | 21,400               | 16.55          | 2    |
| 1109+244   | 37,800               | 16.64          | 3    |
| 1120+439   | 27,200               | 16.28          | 3    |
| 1133+293   | 23,000               | 15.69          | 3    |
| 1214+267   | 65,700               | 16.54          | 3    |
| 1216+036   | 14,400               | 16.66          | 2    |
| 1257+032   | 17,600               | 16.39          | 2    |
| 1507+021   | 20,200               | 17.23          | 2    |
| 1553+353   | 25,600               | 15.59          | 3    |
| 1559+128   | 29,200               | 17.74          | 3    |
| 1620+513   | 20,900               | 16.61          | 1    |
| 2120+054   | 36,200               | 16.93          | 1    |

### Table 4

| Name | $F_{3.6\mu m}$ (μJy) | $F_{4.5\mu m}$ (μJy) | $F_{5.5\mu m}$ (μJy) | $F_{7.8\mu m}$ (μJy) |
|------|----------------------|----------------------|----------------------|----------------------|
| WD 0033−114 | 61 ± 4               | 41 ± 3               |                     |                     |
| WD 0216−095 | 28 ± 2               | 17 ± 2               |                     |                     |
| WD 0309+560 | 60 ± 4               | 37 ± 3               |                     |                     |
| JD951+4033 | 34 ± 3               | 22 ± 2               |                     |                     |
| WD 1035−003 | 53 ± 3               | 36 ± 3               |                     |                     |
| WD 1212−023 | 85 ± 5               | 60 ± 4               |                     |                     |
| WD 1244+498 | 38 ± 3               | 23 ± 2               |                     |                     |
| J1257+4252 | 19 ± 2               | 13 ± 2               |                     |                     |
| J1309+4913 | 38 ± 3               | 24 ± 2               |                     |                     |
| G 199−63   | 57 ± 4               | 37 ± 3               |                     |                     |
| LP 219−80  | 104 ± 7              | 71 ± 5               |                     |                     |
| J2209+1223 | 88 ± 5               | 86 ± 5               |                     |                     |
| J2228+1207 | 156 ± 9              | 104 ± 6              |                     |                     |
| WD 2222+683 | 95 ± 5               | 64 ± 4               |                     |                     |

### Table 5

| WD         | $F_{3.6\mu m}$ (μJy) | $F_{5.7\mu m}$ (μJy) | $F_{7.8\mu m}$ (μJy) |
|------------|----------------------|----------------------|----------------------|
| 0816+297   | 76 ± 5               | 32 ± 7               | 28 ± 5               |
| 0819+363   | 97 ± 5               | 66 ± 8               | 55 ± 10              |
| 0843+516   | 134 ± 9              | 98 ± 10              | 154 ± 13             |
| 0937+505   | 27 ± 3               | 22 ± 7               | 27 ± 4               |
| 1017+125   | 47 ± 6               | 35 ± 4               | 24 ± 3               |
| 1109+244   | 36 ± 4               | 37 ± 4               | 29 ± 4               |
| 1120+439   | 47 ± 4               | 65 ± 11              | 54 ± 4               |
| 1133+293   | 90 ± 6               | 61 ± 13              | 53 ± 16              |
| 1214+267   | 35 ± 3               | 32 ± 3               | 19 ± 3               |
| 1216+036   | 45 ± 3               | 34 ± 3               | 36 ± 3               |
| 1257+032   | 51 ± 4               | 34 ± 11              | 33 ± 4               |
| 1507+021   | 25 ± 3               | 32 ± 3               | 26 ± 3               |
| 1553+353   | 102 ± 6              | 60 ± 7               | 38 ± 9               |
| 1559+128   | 12 ± 2               | 38 ± 2               | 21 ± 2               |
| 1620+513   | 43 ± 3               | 23 ± 3               | 26 ± 3               |
| 2120+054   | 27 ± 3               | 39 ± 3               | 23 ± 3               |
followed by PRF fitting to obtain the true flux of the star. Following instructions in the MOPEX User’s Guide, PRF fitting was performed in individual exposure using the modified Simplex algorithm. A residual mosaic, which subtracted the detected point source from the original mosaic, was produced. To check the result of PRF fitting, aperture photometry was re-performed at the same location of the target in the residual image. A good fit is achieved if the flux level in the aperture is comparable to the sky level, which is a few percent of the flux of the source. Examples of PRF fitting and the residual image are shown in Figures 1 and 2.

For some archived stars, the background is very noisy in the 5.7 \( \mu m \) and 7.9 \( \mu m \) band. We report a positive detection when the measured flux is at least 3\( \sigma \). To measure the upper limit, aperture photometry was performed in 20 empty background regions around the source with an aperture size of 2 native pixels. Then the standard deviation of these fluxes is taken to equal 1\( \sigma \).

The SEDs of all the targets are plotted in Figures 3–10. Also included in the SEDs are \( ugriz \) fluxes from SDSS, \( JHK \) fluxes from the Two Micron All Sky Survey (2MASS), and \( WISE \) fluxes when the data are available. Ultraviolet fluxes from the \textit{Galaxy Evolution Explorer} (GALEX; Martin et al. 2005) are usually excluded because they can be strongly suppressed due to heavy element blanketing (Koester et al. 2011) or interstellar extinction. A blackbody model is then adopted to fit

Figure 1. IRAC mosaics of J2209+1223 in 3.6 \( \mu m \) (the upper panel) and 4.5 \( \mu m \) band (the lower panel) in the plate scale of 1"/2 pixel\(^{-1}\); the left columns are the original data and the right columns are the residue after PRF fitting and the white dwarf is subtracted. North is up and east is left; the field of view is 36" by 36".

(A color version of this figure is available in the online journal.)
the star’s photospheric flux, with most weight given to the SDSS photometry because the 2MASS fluxes have larger uncertainties. Though the blackbody temperature does not always agree with the reported white dwarf temperature of Dufour et al. (2007), this method is sufficient to identify infrared excess that is 10% above the photospheric value. When there is a detected excess, a thin, opaque, passive dusty disk is used to fit the SED (Jura 2003).

3.2. Notes on Individual Stars

3.2.1. WD 0216−095

This star is heavily blended with a nearby galaxy SDSS J021836.98−091955.7 with an angular separation of 2′.6 at position angle 210°. We take a proper motion of 130 mas yr−1 in R.A. and 43 mas yr−1 in decl. from the NOMAD catalog (Zacharias et al. 2005) to derive a position of 02:18:36.77−09:19:44.24 at the epoch of the Spitzer observation. Then we used the method described above to resolve these two objects. No excess is detected for this star.

3.2.2. WD 0936+560

In Figure 3, we see that the 2MASS H-band upper limit is significantly lower than our predicted photospheric flux. Based on the SDSS photometry and the near infrared spectra for this star in Kilic et al. (2008), we assign a very low weight for this point when fitting the SED and no infrared excess is found for this star.

Figure 2. Same as Figure 1 except for G 241−6. We see this is a very complicated field and G 241−6 is heavily blended with an object with an angular separation of only 2′.3 at position angle 170° and another galaxy, J222334.23+683723.8 with a separation of 5′.5 and position angle 110°.

(A color version of this figure is available in the online journal.)
3.2.3. J2209+1223

The IRAC image of this star reveals an unresolved background star separated at 6.2′′ at position angle 333° (see Figure 1). The proper motion of this star is small enough that it is neglected. Robust centroid methods were used in each exposure to accurately determine the position of these two objects, and then PRF fitting was performed. To demonstrate the effectiveness of the PRF fitting, the original image and residue after subtracting the star are shown in Figure 1.

Figure 9 shows the SED for J2209+1223; we see a strong infrared excess in both IRAC bands, which is better explained by a flat disk rather than a companion. In the disk models of Jura (2003), there is a degeneracy between the inclination of the disk and its size. With only two data points, there are two sets of parameters as listed in Table 6 that can reproduce the SED: a more inclined larger disk or more face-on smaller disk. Another good fit to the SED is a blackbody with $T = 1000$ K and $R = 0.3 R_{\odot}$ at the same distance as the white dwarf, 190 pc. However, this derived radius is much too large for a brown dwarf. Furthermore, there is no feature indicative of M dwarf companions, such as H$_\alpha$ emission or TiO absorption lines in the SDSS spectra of this star.

J2209+1223 has an effective temperature of 17,300 K with an accretion rate of $3 \times 10^{10}$ g s$^{-1}$; this value is quite uncertain as it is derived from scaling the equivalent width of magnesium lines from GD 61, which is a white dwarf with similar stellar parameters (Farhi et al. 2011). This star falls into the catalog of highly polluted warm white dwarfs with an infrared excess.
We take the proper motion of G 241−6 as 144 mas yr$^{-1}$ in R.A. and 244 mas yr$^{-1}$ in decl. (Zacharias et al. 2005) to derive its position at 22:23:33.38+68:37:23.8 in the Spitzer observation. In Figure 2, we can see in both IRAC bands that this star is heavily blended with an unknown object at an angular separation of 2$^\prime$.3 at position angle 170$^\circ$. Another galaxy is present at J2233.23+6837.23 at an angular distance of 5$^\prime$.5 and position angle 110$^\circ$. By using PRF fitting, we successfully resolve these objects and no excess is found even though this

### Table 6

| Name          | $T_*$ (K) | $r_*/D$ ($10^{-12}$) | $T_{\text{inner}}$ (K) | $T_{\text{outer}}$ (K) | $r_{\text{inner}}$ ($R_*$) | $r_{\text{outer}}$ ($R_*$) | $\cos i$ |
|---------------|-----------|----------------------|------------------------|------------------------|-----------------------------|-----------------------------|----------|
| WD 0843+516  | 23,900    | 2.2                  | 1260                   | 640                    | 30                          | 75                          | 0.14     |
| J2209+1223    | 15,000    | 1.6                  | 1340                   | 590                    | 15                          | 45                          | 0.55     |
|               | 1.6       | 1080                 | 470                    | 20                     | 60                          |                             | 0.77     |

Note. $^a$ This is the ratio of the stellar radius and its distance to the Sun.

### 3.2.4. G 241−6

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15,300 K star is as heavily polluted as GD 40 (Zuckerman et al. 2010), which does have a dust disk (Jura et al. 2007).

3.2.5. WD 0819+363

In four IRAC bands, this star is blended with the galaxy SDSS J082245.87+361410.2 with a distance of 3.5 at position angle 240° and another unknown object separated at 4.1 and position angle 110°. The proper motion of this star is -78 mas yr⁻¹ in R.A. and -58 mas yr⁻¹ in decl. (Zacharias et al. 2005), and it is located at 8:22:46.2+36:14:12.04 at the epoch of the Spitzer observation. PRF fitting was performed in the 3.6 μm and 4.5 μm band and no excess was found. In the 5.7 μm and 7.9 μm band, the background is so noisy that APEX failed to perform PRF fitting in the nominal position derived from IRAC bands 1 and 2. Instead we used aperture photometry at the position of the star and there appears to be a 3σ excess as shown in Figure 6. However, this is unlikely to be real considering the complicated field.

3.2.6. WD 0843+516

Figure 10 shows the SED for WD 0843+516, apparently the hottest white dwarf so far detected to have a dust disk. The model atmosphere was provided by D. Koester (2011, private communication). An opaque disk model can reproduce the data with the parameters listed in Table 6. As previously found with GD 362 (Jura et al. 2007), the model tends to underpredict the flux at 7.9 μm, which might be contaminated by strong silicate emission in this band. An M dwarf companion can be ruled out as there is no excess in the JHK bands (see Hoard et al. 2007). Another fit to the SED can be achieved with a blackbody of $T = 800 \text{ K}$ and $R = 0.4 R_\odot$ at 140 pc. However, this radius is much too large for a brown dwarf, so this possibility is also excluded. So far WD 0843+516 and WD 1541+650 are the only two white dwarfs with an infrared excess where atmospheric pollution has yet to be measured from suitable spectra.

4. RESULTS

4.1. Missing Planetary Debris around Cool Stars

Warm dust has been found around 22 white dwarfs with temperatures ranging from 9500 K to 24,000 K and at least 20 of them have a highly polluted atmosphere. Between 1% and 3% single white dwarfs with cooling ages less than 0.5 Gyr possess warm circumstellar dust (Farihi et al. 2009). In contrast, the disk fraction around cool white dwarfs ($T_\ast < 6000 \text{ K}$) only has an upper limit of 0.8% (Kilic et al. 2009). Previously, 11 DZs have been targeted with Spitzer/IRAC (Farihi et al. 2008a, 2008b, 2009), but none shows an infrared excess. In this study, we observed 10 additional DZs, which are heavily polluted and most likely disk-host stars. Though almost doubling the numbers of DZs, we still fail to find any infrared excess. We address the implications and possible explanations in Sections 5 and 6.

4.2. Hot White Dwarfs with a Close-in Disk

As discussed by von Hippel et al. (2007), we need to understand how solid dust grains can survive around hot white dwarfs. Dust disks have been confirmed around four stars with stellar temperature higher than 20,000 K: WD 0843+516 (this paper), GALEX 1931 (Debes et al. 2011a), PG 1457–086 (Farihi et al. 2009), and WD 1226+110 (Brinkworth et al. 2009). Currently, there are two different models to describe the inner boundary of the disk: a fully opaque disk model (Jura 2003) and an opaque disk with a thin transition zone, which goes from optically thin to optically thick (Rafikov 2011a). However, for the hot white dwarfs, only the opaque disk model allows the inner boundary of the disk to be within the tidal radius,

$$r_{\text{inner}} = \left(\frac{2}{3\pi}\right)^{1/3} \left(\frac{T_s}{T_\ast}\right)^{4/3} r_\ast,$$

where $T_s$ and $r_\ast$ are the stellar temperature and radius, respectively. $T_\ast$ is the temperature at which the dust particles sublimate; it can be constrained from the 3.6 μm excess and is usually 1200 K (see, for example, Jura et al. 2007). So for a 20,000 K star, the inner boundary for a complete opaque disk is 25 $r_\ast$.

In the model described by Rafikov (2011a), the inner boundary of the optically thin region is

$$r_{\text{inner}} = \frac{r_\ast}{2} \left(\frac{T_s}{T_\ast}\right)^2.$$

For a 20,000 K star, the inner radius is 140 $r_\ast$, whereas the tidal radius is approximately 130 $r_\ast$ (von Hippel et al. 2007). In this case, all the dust particles lie outside of the tidal radius.

We have no way to resolve the disk and directly tell which model is correct, but the fully opaque disk model is the simplest explanation for the presence of close-in dust. There are two additional arguments in favor of the opaque disk model: it can reproduce the substantial amount of infrared excess and the dust disk radii agree with those derived from gaseous emission lines (Gänsicke et al. 2006; Melis et al. 2010). Further discussion is presented in the Appendix, where we consider P-R drag on a completely opaque disk described by Jura (2003) and derive an accretion rate that agrees better with the data than the model described in Equation (2) (Rafikov 2011a).

5. CHARACTERISTICS OF DISK-HOST STARS

We see the planetary debris seems to be missing around the polluted cool stars. Why is that? In this section, we explore different characteristics that might be correlated with the occurrence of a dust disk.

5.1. High Heavy Element Accretion Rate?

It is found that at least 50% of white dwarfs with heavy element accretion rates over $3 \times 10^{-6} \text{ g s}^{-1}$ have warm dust (Farihi et al. 2009). But cool stars do not appear to follow this
Figure 6. SED for archived targets, including data from SDSS, 2MASS, IRAC, and WISE data when available with 2σ error bars. The asterisks denote the upper limit. The dashed line is a simple blackbody fit to the photospheric flux.

pattern. Figure 11 shows a comparison of the overall accretion rate with a white dwarf's stellar temperature. We see that there are numerous cool white dwarfs ($T_\ast < 10,000$ K) that have an accretion rate higher than $3 \times 10^8$ g s$^{-1}$, but none displays a dust disk.

To calculate the accretion rate of element A, we assume a steady state so that it equals the mass of A in the convective zone divided by its settling time. For the stars that have well-determined major element abundances, the accretion rate is simply the sum of all the heavy elements. For the stars that have both magnesium and iron abundance, we assume that they are 30% of the total mass of the parent body. For the Cycle 7 targets, calcium is the only detected heavy element and we assume it is 0.6% of the total mass, extrapolated from the cool DZs in Koester et al. (2011). All the stellar parameters are extrapolated from Koester (2009) and Koester et al. (2011).

5.2. Massive Parent Bodies?

Another possibility is that while more massive parent bodies can form a dusty disk, less massive parent bodies can only form a more tenuous, short-lived dust disk or a purely gaseous disk (see Jura 2008). A comparison of the mass of heavy elements in the atmosphere versus the white dwarf's effective temperature is shown in Figure 12. We see there is no difference in the mass in the convective zone, $M(Z)$, between stars with and without an infrared excess. An uncertainty is that the masses plotted in Figure 11 are only lower bounds since we do not know how long
Figure 7. Same as Figure 6.

5.3. Refractory-rich Parent Bodies?

Jura & Xu (2012) argue that there are at least two populations of parent bodies that are accreted onto a white dwarf: water-rich comet-like objects and dry rocky objects. Here we suggest that the compositional variations of the accreted materials might be important in the formation of a dust disk. A comparison between calcium, magnesium, and iron accretion rates is plotted in Figure 13. log \( \dot{n}(\text{Ca})/\dot{n}(\text{Mg}) \) and log \( \dot{n}(\text{Fe})/\dot{n}(\text{Mg}) \) versus the star's temperature are shown in order to correct for different settling rates. These values correspond to the intrinsic abundance ratio in the parent body assuming a steady state.

We see in the upper panel of Figure 13 that most stars with an infrared excess have a relatively high abundance of Ca, a highly refractory element (Allègre et al. 2001); the average \([\text{Ca}]/[\text{Mg}]\) in these stars is \(-0.71\) while it is \(-1.21\) in bulk Earth. In contrast, when measured in a different sample of DZs than studied here, \([\text{Ca}]/[\text{Mg}]\) equals \(-1.42\) (Koester et al. 2011). In the lower panel of Figure 13, we see Fe abundance almost stays the same. Since iron is one of the dominant elements in the bulk Earth as well as the white dwarf pollution (Klein et al. 2010), there is no reason to think its abundance should vary much. There is additional evidence supporting that cool white dwarfs are accreting more volatile-rich materials. Sodium, which is an important volatile,
has a nearly solar abundance in 28 extreme DZs, much higher than the bulk Earth value (Koester et al. 2011; Allègre et al. 2001).

6. ORIGIN OF HEAVY ELEMENTS IN STARS WITHOUT AN INFRARED EXCESS

We see most polluted white dwarfs do not possess a dust disk. So where do the heavy elements come from? Interstellar accretion was traditionally considered to be the origin of this material (Dupuis et al. 1993) but this model has faced many challenges (Farihi et al. 2010a; Koester et al. 2011). We discuss two avenues of accretion that can pollute a white dwarf’s atmosphere without producing a dust disk.

Accretion from a distant reservoir. It has been suggested that some comets go through natural fragmentation due to fast rotation (Drahus et al. 2011) and in this way contribute to the zodiacal light in our solar system (Nesvorný et al. 2010). A similar process might happen around a white dwarf given that there might be a large reservoir of comets. Eventually some of the dust particles will drift inward due to P-R drag and the amount of infrared flux produced at frequency $\nu$ is (Jura et al. 2007)

$$F_\nu \approx \frac{1}{2} \ln \left( \frac{R_i}{R_f} \right) \frac{\dot{M}(Z)c^2}{\nu} / 4\pi D^2,$$

where $R_i$ and $R_f$ are the initial and final distance of the accretion and $R_i/R_f$ is taken to be 1000, $\dot{M}(Z)$ is the total accretion rate, $c$ is the speed of light, and $D$ is the distance between the Sun and the white dwarf. We compare the flux predicted from Equation (3) with our data for Cycle 7 targets in Table 7. For the heavily polluted Cycle 7 targets, we see that the calculated flux is always much higher than the observed value. However, there are other cool white dwarfs with an accretion rate $\sim 10^6$ g s$^{-1}$ (Farihi et al. 2009) where this process might be important.

Accretion from an orbiting gaseous disk. A gaseous disk that does not emit too much in the infrared can be formed if the grains mutually annihilate as described in the model of Jura (2008) or the objects sublimate as they get close to the white dwarf. This is likely to be true for DAZs warmer than 11,000 K
Figure 10. SED for WD 0843+516. The green line displays the model atmosphere (D. Koester 2011, private communication), the blue line the model disk, and the black line the sum of both. The upper panel shows the entire fit to the model atmosphere while the lower figure only shows the disk portion. The pink dots are taken from GALEX, SDSS, and 2MASS, green dots from WISE, and red dots from IRAC, respectively; 2σ error bars are displayed.

(A color version of this figure is available in the online journal.)

Table 7
Infrared Flux Produced by Accretion from Cometary Dust

| Name          | D (pc) | log $\dot{M}(Z)$ (g/s) | $F_{\nu,4.5}$ (μJy) Predicted* | Observed |
|---------------|--------|------------------------|---------------------------------|----------|
| WD 0033−114   | 55     | 8.66                   | 6300                            | 41 ± 3   |
| WD 0216−095   | 97     | 7.34                   | 120                             | 17 ± 2   |
| WD 0936+560   | 65     | 9.41                   | 25,000                          | 38 ± 2   |
| J0951+4033    | 84     | 7.69                   | 310                             | 22 ± 2   |
| WD 1035−003   | 49     | 9.65                   | 77,000                          | 37 ± 2   |
| J1309+4913    | 83     | 7.76                   | 370                             | 24 ± 2   |
| G 199−63      | 68     | 8.53                   | 3100                            | 37 ± 2   |
| LP 219−80     | 45     | 6.61                   | 160                             | 71 ± 4   |
| J2228+1207    | 34     | 7.96                   | 3200                            | 105 ± 6  |

Notes. This table contains all the Cycle 7 stars with reported distance (Dufour et al. 2006).
* These values are the predicted total flux, which is the sum of the photospheric flux and the excess due to accretion from the cometary dust.

because their settling time is only days (Koester 2009). Without the continuous feeding of material, the elements would have quickly settled.

7. CONCLUSIONS

We find two new stars with an infrared excess, J2209+1223 and WD 0843+516, apparently the hottest white dwarf with a close-in disk. We fail to find any warm dust around heavily polluted DZs, all of which have $T_\ast < 10,000$ K. We raise the possibility that there might be some correlation between the occurrence of dust disk and the volatility of the accreted material. The best model for explaining the source of pollution in white dwarfs without an infrared excess has yet to be established.

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APPENDIX

In this Appendix, we extend the model of Rafikov (2011a) for P-R drag on the entire disk to account for the observed mass accretion rates. Our modification of his model leads to a better agreement with the data.

Assuming a steady state, the accretion rate provided by P-R drag is (Rafikov 2011a)

$$M(r_{inner}) = \frac{16\phi_r}{3} \frac{r_{inner}^3}{c^2} \sigma T_s^4,$$  \hfill (A1)

where $\sigma$ is the Stefan–Boltzmann constant, $c$ is the speed of light, and $\phi_r$ is an efficiency coefficient.

Using Equation (2), Rafikov (2011a) derived an accretion rate,

$$M(r_{inner}) = \frac{32\phi_r}{3} \sigma \left( \frac{r_s T_s}{c} \right)^2 \left( \frac{T_s}{15,000 \text{ K}} \right)^2 g \text{ s}^{-1}. \hfill (A2)$$

In the last step, we take $r_s = 0.013 R_\odot$ and $\phi_r = 1$.

As discussed in Section 4.2, our inner boundary is described by Equation (1); so we get a different value of accretion rate,

$$M(r_{inner}) = \left( \frac{3\pi}{2} \right)^{1/3} \frac{16\phi_r}{3} \sigma \left( \frac{r_s}{c} \right)^2 \left( \frac{T_s}{T_s^2} \right)^{2/3} \left( \frac{T_s}{15,000 \text{ K}} \right)^{8/3} g \text{ s}^{-1}. \hfill (A3)$$

A comparison between these two accretion rates is shown in Figure 14 and we see they differ as much as a factor of five. Observationally, we can also derive the accretion rate from the atmospheric pollution. Since we are trying to make a comparison between models that vary by a factor of five, we need accurate abundances. Therefore, we only consider stars that have measurements for at least three of the four major elements in white dwarf pollution (Klein et al. 2010): O, Mg, Si, and Fe. In Figure 14, we see that the accretion rates derived from our model and spectroscopical analysis agree well for DAZs. Since the settling time for heavy elements is relatively short in these stars, the presence of a dusty disk indicates that the accretion should be in a steady state (Koester 2009), which satisfies the assumption of the calculation above. For DBZs, the settling time is comparatively longer and we cannot determine whether the system is in the buildup phase or steady state. The accretion rate driven by PR drag gives a good lower bound in

Figure 13. Compositional difference for all the stars in Figure 11 that have Ca, Mg, and Fe detections. The relative abundance has been corrected for settling assuming a steady state. The dashed line is the value for the bulk Earth. We see the stars with infrared excess usually have a high $\delta$(Ca)/$\delta$(Mg).

(A color version of this figure is available in the online journal.)

Figure 14. Mass accretion rate onto white dwarfs with an infrared excess. The solid line shows the value predicted by our model while the dashed line is the value derived in Rafikov (2011a). The DAZs are G29–38 (Koester 2009) and GALEX 1931 (Vennes et al. 2011). And DBZs are GD 40 (Klein et al. 2010), GD 61 (Farihi et al. 2011), SDSS J0738 (Dufour et al. 2010), PG 1225–079 (Klein et al. 2011), Ton 345 (D. Koester 2011, private communication), and GD 562 (Koester 2009). All the stars in this figure have well-determined major element abundance.
these stars and there might be other mechanisms on top of that, as discussed in Rafikov (2011b).

Note added in proof. Farihi et al. (2012) have used warm Spitzer to confirm that three of the candidate sources listed in Table 1 have circumstellar disks.

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