COOL CUSTOMERS IN THE STELLAR GRAVEYARD. III. LIMITS TO SUBSTELLAR OBJECTS AROUND NEARBY WHITE DWARFS USING THE CANADA-FRANCE-HAWAI'I TELESCOPE

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ABSTRACT

Results from a ground-based high-contrast imaging survey of 13 nearby white dwarfs for substellar objects are presented. We place strict upper limits on the type of substellar objects present, ruling out the presence of anything larger than $\sim 14 M_J$ for eight of the white dwarfs at separations $> 19$ AU and corresponding to primordial separations of $\sim 3$–6 AU assuming adiabatic mass loss without tidal interactions. With these results we place the first upper limit on the number of intermediate-mass stars with brown dwarfs at separations $> 13$ AU. We combine these results with previous work to place upper limits on the number of massive Jovian ($> 10 M_J$) planets in orbit around white dwarfs whose progenitors spanned a mass range of 1–7 $M_\odot$.

Key words: circumstellar matter — planetary systems — white dwarfs

1. INTRODUCTION

White dwarfs (WDs), the end state of stellar evolution for stars of mass $\sim 1–8 M_\odot$, are a population of stars that potentially hold an important key to directly imaging extrasolar planets (Burleigh et al. 2002). They present several advantages compared to main-sequence stars for strategies that rely on high-contrast imaging. Due to their dense nature, WDs have small radii and cooling atmospheres that translate to surface fluxes that are orders of magnitude dimmer than their main-sequence progenitors. Since it is hotter than any putative substellar companion, the companion’s flux peaks well into the Rayleigh-Jeans tail of the WD’s emission. These two factors allow a modest contrast difference between the WD and any possible substellar companions.

This is the third paper in a series that takes slightly different approaches in the attempt to directly image a nearby extrasolar planet and place limits on what type of companions could be present around each WD. The first, Debes et al. (2005a, hereafter DSW05a), looked specifically at the WD G29-38 but hereafter DSW05b), relied on 2MASS data and constrain the presence of planets and brown dwarfs at distances of $\sim 3$–6 AU assuming adiabatic mass loss without tidal interactions. With these results we place the first upper limit on the number of intermediate-mass stars with brown dwarfs at separations $> 13$ AU. We combine these results with previous work to place upper limits on the number of massive Jovian ($> 10 M_J$) planets in orbit around white dwarfs whose progenitors spanned a mass range of 1–7 $M_\odot$.

2. OBSERVATIONS

Observations of all the WDs were taken during three trips to CFHT, the first on 2003 October 11–14, the second on 2004 April 1, and the last on 2004 September 29. Observations were taken primarily in the J band on the first run and in the H band on the second and third runs using the KIR instrument in conjunction with PUEO, the wave front curvature adaptive optics (AO) system (Rigaut et al. 1998). Table 1 shows the list of targets including their $V$ magnitudes, masses, primordial masses, estimated ages, effective temperatures, and distances. The mass, $T_{\text{eff}}$, and cooling age came from either Bergeron et al. (2001) or Liebert et al. (2005), with the exception of WD 0501+527. WD 0501+527’s parameters come from Finley et al. (1997). The primordial mass ($M_\text{f}$) was calculated by a theoretical initial-to-final mass function given by $M_\text{f} = 10.4 \ln [(M_{\text{WD}}/M_\odot)0.49] M_\odot$ (Wood 1992). The main-sequence lifetime of the star was determined by $t_{\text{MS}} = 10 M_\odot^{-0.5}$ Gyr (Wood 1992). Since these relations only work well for $M_{\text{WD}} > 0.54 M_\odot$, WD 0501+527’s total age is unknown.

The very advantage these targets have for detecting planets is offset by the fact that most current AO systems cannot reliably correct for atmospheric turbulence for such faint objects. With most large-telescope AO systems requiring targets with $V \lesssim 13$, most of these targets would have to be imaged without the help of AO. However, the curvature wave front sensor AO system of PUEO provides a heightened advantage by being able to track targets with $V \lesssim 16$, allowing most nearby WDs to be accessible to AO correction (Rigaut et al. 1998). AO correction is particularly useful for gaining spatial resolution, as well as sensitivity.
against the near-IR background, the wavelength at which cool substellar objects become observable with current telescopes. These two benefits allow the more modestly sized CFHT to compete realistically with larger telescopes in this area without AO, as well as with space-based near-IR imaging.

Table 2 shows our list of observations, as well as total integrations for each target WD. Most objects were observed for ~1 hr using 240 s subexposures that were dithered in a 5" five-point grid pattern for background subtraction. This left an ~20" x 20" field of high sensitivity. WD 1213+568 and WD 1633+572 had shorter total exposure times, with 15 and 16 minutes, respectively. WD 0208+396, WD 0501+527, and WD 2341+321 had longer integrations of 90, 66, and 78 minutes, respectively. During these observations high levels of relative humidity forced the telescope to be shut down for short periods of time, which resulted in a repetition of some positions of our dither pattern on the sky. Objects that threatened to saturate the detector had shorter subexposures. This was the case for WD 1213+568 and WD 2140+207, whose subexposures were 60 and 120 s, respectively. WD 0501+527's final FWHM was limited FWHM of 120 mas. WD 0501+527's final FWHM was 138 mas, compared to the 2MASS system to the Mauna Kea Observatories (MKO) magnitude of the WD, taking into account the transformation from the 2MASS system to the MKO system.

Correction deteriorated toward dawn on our second run as the sky background increased, and weather conditions varied throughout our first run. The third run had spectacular seeing throughout most of the night (0.5–0.6" in V), allowing diffraction-limited images to be taken of WD 2140+207, WD 2246+223, and WD 2341+321. Throughout much of the second run, when most of our targets were taken, the FWHM of our final images ranged from ~140 to ~200 mas, compared to a diffraction-limited FWHM of 120 mas. WD 0501+527's final FWHM was 132 mas, compared to the J-band diffraction-limited FWHM of 90 mas.

3. DATA ANALYSIS

All data were flat-fielded, background-subtracted, registered, and combined into final images. These final images were used for two purposes: for deep background-limited imaging far from the central target star and as point-spread function (PSF) reference stars for other observations. Due to dithering, the highest sensitivity was generally within 7" of the target star.

In order to gain contrast close to each target WD, we also employed PSF subtraction to get high contrast to within 1". To achieve good results, each registered subexposure was subtracted from another reference PSF image, preferably from a reference that was brighter than the target and had a similar FWHM. The subtraction images were median combined to produce the final subtracted image. In the case of WD 1121+216 and WD 1953+011 there was a brighter star in the field that was used as a simultaneous reference. Even though observations were separated by timescales on the order of hours, we were able to get subtraction that depressed the PSF by 3–4 mag at 0.78 (see Fig. 1), with a higher sensitivity typically achieved in the non-subtracted images beyond 2". PSF subtraction was not possible for WD 1213+528, WD 0208+396, and WD 0521+527, since no suitable reference was available. Figure 1 shows a comparison before and after PSF subtraction with a contemporaneous reference for WD 1953+011.

Any point sources that were detected had their flux measured by adding the counts within an aperture comparable to the FWHM of the particular image and comparing the counts in the same size of aperture with the target star. A differential H magnitude was computed and then added to the 2MASS H magnitude of the WD, taking into account the transformation from the 2MASS system to the Mauna Kea Observatories (MKO)

### Table 1: List of WD Targets

| WD          | V     | $M_V$ | $M_K$ | $T_{eff}$ | D   | Total Age | References |
|-------------|-------|-------|-------|-----------|-----|-----------|------------|
| 0208+396    | 14.5  | 0.60  | 2.1   | 7310      | 16.7| 2.9       | 1          |
| 0501+527    | 11.8  | 0.53  |       | 61000     | 68.8| 2.8       | 2          |
| 0912+536    | 13.8  | 0.75  | 4.4   | 7160      | 10.3| 2.8       | 1          |
| 1055+072    | 14.3  | 0.85  | 5.7   | 7420      | 12.2| 3.0       | 1          |
| 1121+216    | 14.2  | 0.72  | 4.0   | 7490      | 13.4| 2.2       | 1          |
| 1213+528    | 13.3  | 0.64  | 2.8   | 13000     | 38.6| 1.0       | 3, 4       |
| 1334+039    | 14.6  | 0.55  | 1.2   | 5030      | 8.2 | 10.2      | 1          |
| 1626+368    | 13.8  | 0.60  | 2.1   | 8640      | 15.9| 2.6       | 1          |
| 1633+433    | 14.8  | 0.68  | 3.4   | 6650      | 15.1| 2.8       | 1          |
| 1633+572    | 15.0  | 0.63  | 2.6   | 6180      | 14.4| 3.8       | 1          |
| 1953+011    | 13.7  | 0.74  | 4.3   | 7920      | 11.4| 1.9       | 1          |
| 2140+207    | 13.2  | 0.62  | 2.4   | 8860      | 12.5| 2.1       | 1          |
| 2246+223    | 14.4  | 0.97  | 7.1   | 10330     | 19.0| 1.7       | 1          |
| 2341+321    | 12.9  | 0.57  | 1.6   | 12570     | 16.6| 3.4       | 3          |

### Table 2: Observations

| WD          | Date       | Time (UTC) | Filters | Total Integration (s) |
|-------------|------------|------------|---------|-----------------------|
| 0208+396    | 2004 Sep 30| 11:10:46   | H       | 5280                  |
| 0501+527    | 2003 Oct 11| 14:22:43   | J       | 3840                  |
| 0912+536    | 2004 Apr 2 | 06:33:58   | H       | 3600                  |
| 1055+072    | 2004 Apr 2 | 08:12:16   | H       | 3600                  |
| 1121+216    | 2004 Apr 2 | 09:24:38   | H       | 3600                  |
| 1213+528    | 2004 Apr 2 | 10:47:20   | H       | 900                   |
| 1334+039    | 2004 Apr 2 | 11:32:37   | H       | 3600                  |
| 1626+368    | 2004 Apr 2 | 12:46:04   | H       | 3600                  |
| 1633+433    | 2004 Apr 2 | 14:13:36   | H       | 3600                  |
| 1633+572    | 2004 Apr 2 | 15:22:16   | H       | 960                   |
| 1953+011    | 2004 Sep 30| 05:09:33   | H       | 3600                  |
| 2140+207    | 2004 Sep 30| 06:27:51   | H       | 3600                  |
| 2246+223    | 2004 Sep 30| 07:44:44   | H       | 3600                  |
| 2341+321    | 2004 Sep 30| 09:56:37   | H       | 4680                  |
system. Since AO PSFs tend to vary with time, photometric accuracy is limited by this variation, and we found it preferable to use differential magnitudes, since to zeroth order all PSFs in an image should be varying in the same manner. The large isoplanatic patch of PUEO makes this a reasonable assumption in an image should be varying in the same manner. The large accuracy is limited by this variation, and we found it preferable in a system. Since AO PSFs tend to vary with time, photometric accuracy is limited by this variation, and we found it preferable to use differential magnitudes, since to zeroth order all PSFs in an image should be varying in the same manner. The large isoplanatic patch of PUEO makes this a reasonable assumption in an image should be varying in the same manner.

**4. CANDIDATE COMPANIONS AND BACKGROUND OBJECTS**

Many targets showed nothing besides the primary in the field of view. However, six of the targets had other objects in the field that we designated as potential candidates. Any candidate would have to be unresolved. Where second-epoch images were available, we used them to determine whether any candidate was co-moving with the primary. If any second-epoch images showed no common proper motion, that candidate was eliminated. Two candidates do not have second-epoch information and remain as viable brown dwarf candidates. Several of the higher latitude targets also had nearby resolved galaxies within 10°, which we note in case they are useful for future ground-based study, such as with laser-guided AO or multiconjugate AO. Table 3 gives their positions and $H$-band magnitudes within a 0′5 aperture. One object, DSW 1, has already been presented in DSW05b, but here we add its MKO $H$ magnitude from our CFHT observations.

**4.1. WD 2341+321**

WD 2341+321 has two candidate point sources, C1 and C2, that cannot be refuted with second-epoch POSS images. Both are too faint to have been detected. C1 is at a radius (R) of 9′17 ± 0′01 and a position angle (P.A.) of 116° ± 1°, with an $H$ magnitude of 18.5. The source C2 is detected closer in, after PSF subtraction. Figure 2 shows the original image and the same image after PSF subtraction. This dimmer candidate is more promising, since it is closer to the target WD and is detected at a signal-to-noise ratio (S/N) of 7 with an $H$ magnitude of 22.3. It has $R$ = 2′25 and P.A. = 72°5 ± 1°. If both were physically associated with WD 2341+321, they would have masses of $27M_J$ and $13M_J$, respectively. At a distance of 16.6 pc they would have orbital separations of 37 and 152 AU, corresponding to primordial separations of 13 and 54 AU given a current WD mass of 0.57 $M_\odot$ and an inferred initial mass of 1.6 $M_\odot$. However, they cannot be ruled associated until they demonstrate common proper motion with WD 2341+321. WD 2341+321’s proper motion is 0′21 yr$^{-1}$, so it should be relatively easy to determine common proper motion within a year (Perryman et al. 1997).

**4.2. WD 1121+216**

WD 1121+216 has a brighter star ~5″ away. Inspection of POSS plates clearly shows that it is a relatively fixed background star and not a common proper motion companion. After PSF subtraction, WD 1121+216 shows emission that at first glance appears to be a dust disk or blob ~20 AU from the WD. Figure 3 shows the emission. It is clearly visible both in the original image and after PSF subtraction. Inspection of the POSS II $B$ plate shows that it is most likely a background galaxy, as there is an extended source at the position of the emission currently seen near the WD. Caution should be taken with high-latitude objects that appear to show extended emission, as a background galaxy can be mistaken for circumstellar emission. Any such discovery should show common proper motion to be credible. The background galaxy has a surface brightness of 20.1 mag arcsec$^{-2}$. This detection demonstrates that we could have discovered any circumstellar emission for our targets at approximately this level.

**4.3. WD 1213+528**

WD 1213+528 shows a candidate companion ~8″ to the south, but inspection of POSS II plates shows that this object is not a common proper motion companion.

**4.4. WD 1953−011**

WD 1953−011 has several nearby background sources, which are well separated. Most are visible on POSS plates and due to WD 1953−011’s proper motion are easily discarded as possible proper motion companions. The brightest background object in the field, ~7″ to the south, has a noticeable companion at a separation of 1′30±0′01, P.A. = 88°6 ± 0°3, with $\Delta H = 7.6$. Figure 4 shows the star before and after PSF subtraction and Gaussian smoothing.

A spectrophotometric spectral energy distribution using POSS $B$, $V$, $R$, and $I$ magnitudes and 2MASS $J$, $H$, and $K_s$ magnitudes of the background star makes it consistent with either an M0 dwarf at ~300 pc or a K2 giant at ~10 kpc (Allen & Cox 2000). If it were a main-sequence star, the companion would be a 0.07−0.08 $M_\odot$ object according to the models of Baraffe et al. (2003). If it were instead a giant, the companion
would be an M dwarf. The former explanation of a nearby M dwarf host star with a low-mass companion seems more plausible given the low Galactic latitude of the source and the apparent lack of significant reddening. It is also possible that the two stars are not physically associated. Despite the fact that this is not relevant to our current study, this discovery demonstrates the efficacy of our PSF-subtraction technique.

4.5. WD 2140+207

WD 2140+207 has a dim, pointlike object ~5″ away, with several point sources and galaxies in the surrounding field. Most of the point sources can be discriminated as background objects from POSS plates, including the near object discovered. With the help of POSS PSF subtraction, a marginal detection of the companion was possible on the POSS II B plate. At epoch 1990.57, the time of the observations taken by POSS, the separation of the object was \( R = 8'^{5}58 \) with P.A. = 239.6 east of north. In our CFHT observations the object was at \( R = 5'^{5}88 \) and P.A. = 296.7. This is clearly a background object.

4.6. WD 0208+396

Two candidate objects, as well as a galaxy ~8″ away, were discovered in HST images presented in DSW05b. The point-source candidates were reimaged on our third visit to CFHT ~1 year later, and their \( H \) magnitudes were measured. Figure 5 shows the images at the two epochs. C1 and C2 had \( H \) magnitudes of 19.35 and 22.22, respectively. In order to determine whether any of the candidates had common proper motion we needed to compare their positions relative to the HST observations in DSW05a. In those observations C1 was found to be at a separation of \( 8'^{6}0 \pm 0'^{1}1 \) and P.A. = 175° ± 1°. Its F110W magnitude was 20.64 ± 0.01. WD 0208+396 has a proper motion of 1069 mas yr\(^{-1}\) in right ascension and ~523 mas yr\(^{-1}\) in declination, which allows us to predict the position of C1 if it is not comoving. We predict C1’s position with respect to WD 0208+396 to be \( \Delta R.A. = -0'^{0}41 \pm 0'^{0}1, \Delta \text{decl.} = -8'^{0}03 \pm 0'^{0}1 \). We find that the candidate is measured at a position \( \Delta R.A. = 0'^{0}03, \Delta \text{decl.} = -8'^{0}02 \). C2 has an F110W magnitude of 23.5 ± 0.1 and in the HST image had \( R = 10'^{0}33 \pm 0'^{0}2 \) with P.A. = 169° ± 2°. Its predicted position if not comoving was predicted to be \( \Delta R.A. = 0'^{0}82 \pm 0'^{0}1, \Delta \text{decl.} = -9'^{0}60 \). The measured relative position was \( \Delta R.A. = 1'^{0}27, \Delta \text{decl.} = -9'^{0}51 \). There is a systematic, significant difference between the predicted \( \Delta R.A. \) and that measured for both candidates, which are also spatially close. Measurements of the relative position of the galaxy in the field also show a similar discrepancy in where its relative position

![Fig. 2.—Candidate companion (C1) at a separation of 2″.5. If this object were physically associated it would be an 11MJ object.](image)

![Fig. 3.—Extended emission discovered around WD 1121+216 before (left) and after (right) PSF subtraction. Second-epoch POSS images show that it is a background galaxy. The scale bar in the left panel represents 2″.](image)
should be (it is obviously not comoving), which supports the explanation that the CFHT field is rotated clockwise by $\sim 1.7$, this places all the measured positions within the errors of the predicted positions. Therefore, we can state with certainty that the candidates are both background objects.

5. LIMITS TO COMPANIONS

Since many targets did not have any possible companions, it is instructive to place limits on what kind of objects could be detected around each target. We can place limits both for resolved and unresolved companions by the combination of our imaging results and the measurement of these objects’ measured fluxes in comparison with their expected fluxes.

5.1. Imaging

For our images, we followed the same strategy for determining our imaging sensitivity as in DSW05a and DSW05b. This strategy is to implant artificial companions into our images and try to recover them at a S/N of 5 in order to test the sensitivity of our observations. The main difference for AO imaging is that

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**Fig. 4**.—Images of a nearby background star near WD 1953–011 that show a companion with $\Delta H = 7.6$ with a separation of $1''08$ before (left) and after (right) PSF subtraction. This detection demonstrates the study’s sensitivity to point sources close to our targets.

**Fig. 5**.—Comparison between the HST and CFHT fields for WD 0208+395. The HST field is on the left, and the CFHT field is on the right. The images are about 9\degree long on a side and show one of the candidates due south of WD 0208+396, which is masked.
the PSF is not stable, so we use a version of our target WD PSF normalized to 1 DN. The implant was scaled by a value and placed within the field, and an aperture approximately equal to the implant’s core FWHM was used to determine the S/N. If the S/N was >5, then the implant was considered recovered; otherwise, the implant’s scaled value was increased. Values at 20 different angular locations were determined at each radius for azimuthal averaging. The median of the different values was taken to give a final azimuthal averaged sensitivity. Relative photometry with respect to the target WD (or another unsaturated object in the field) was calculated, and the 2MASS H magnitude for the target WD was used to determine a final sensitivity. Figure 6 shows a typical sensitivity curve with PSF subtraction.

The values were then used with a grid of substellar spectral models to determine what kind of substellar object a limiting magnitude would correspond to at the particular distance and age of the WD system. Specifically, we used the models of Baraffe et al. (2003), primarily because they had isochrones that spanned the mass range and age of interest to our target WDs. The magnitudes were cross-checked with the models of Burrows et al. (2003), and for isochrones that overlapped they provided similar results to within 1 mag or to within 1M\(_J\) or 2M\(_J\), thus giving us confidence that we could combine our results here with those in DSW05b. Using interpolation, we turned the observed sensitivities to specific masses at the particular ages of the WDs. Table 4 shows the final sensitivities for each WD.

### 5.2. Near-IR Photometry

While direct imaging is most sensitive to companions >1″, unresolved companions could still be present for some of these targets. In order to rule out companions at separations at which imaging or PSF subtraction could not resolve them, we turn to the near-infrared fluxes of these objects provided by 2MASS photometry.\(^5\) Using the measured effective temperatures, gravities, and distances of the WDs given in the literature, we can model the expected J, H, and K\(_S\) fluxes based on the models of Bergeron et al. (1995). If the photometry is of a high enough accuracy, one can place limits on the type of excesses present for these objects. These limits allow us to understand what types of companions and dusty disks are ruled out. The details of this process have already been described in DSW05a. For our targets, the one exception is WD 0501+527, whose parameters are taken from Finley et al. (1997). The distance to WD 0501+527 is determined from its Hipparcos parallax (Perryman et al. 1997). In the Finley et al. (1997) sample only spectroscopic properties were determined, so no attempt to model the distance was made. Due to a lack of modeled distance, we cannot estimate the rough error in the modeling as an ensemble. Rather, we compare \(\Delta J\) to the quoted photometric errors in 2MASS. The errors in J are ~0.02, and since \(\Delta J\) falls within this range we use this as our estimate for a significant excess, which we determine to be an excess of 0.06 in J. Since WD 0501+527 is so hot, its cooling time is <<1 Gyr, and its total age depends entirely on its initial mass. Unfortunately, this is unknown, so we calculate possible companion limits given a range of possible main-sequence ages for this WD.

All our other objects show no significant excess as well, so we need to determine to what mass limit we could have detected an excess in our sample. Taking the substellar models of Baraffe et al. (2003), we took the 3 \(\sigma\) limits and interpolated between the models to fit the estimated total ages of the WD targets. We find that for all our targets, any object more massive than ~69M\(_J\) would have been detectable in the 2MASS search. Therefore, all targets should not have any stellar companions present at close separations. The exceptions to the limit are WD 1213+568, which already has an unresolved companion M dwarf, and WD 0501+527, for which observations are less sensitive due to the large \(T_{\text{eff}}\). Any further excess beyond the companion of WD 1213+568 cannot be determined. Table 4 shows our results for unresolved and resolved companion sensitivities. For the excess limits we take into account the distance to the WD to obtain a limit on the absolute magnitude of an object that could create an excess.

### 6. DISCUSSION

We have surveyed 13 WDs for substellar objects. From this search we have found two potential candidates, both around WD 2341+321. This star requires follow-up observations to confirm or refute these candidates. If any of the companions are

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\(^5\) Vizier Online Data Catalog, 2246 (R. M. Cutri et al., 2001).
confirmed to be comoving, they are dim enough to be consistent with substellar mass objects. To date, only two substellar objects are known to be in orbit around nearby WDs (Zuckerman & Beekin 1992; Farihi & Christopher 2004). With putative absolute magnitudes in the $H$ band of $\sim 21-22$, these would be hard to confuse with higher mass objects such as those in young stellar populations (Mohanty et al. 2004).

To date, nine hydrogen WDs with metal lines, so-called DAZs, have been searched for substellar objects, seven from our observations with HST and two from the ground. WD 1633+433 and WD 1213+529 have both been found to have small amounts of metals such as Ca in their atmospheres (Zuckerman et al. 2003). WD 1213+529 has an unresolved stellar companion, while WD 1633+433 appears from its 2MASS photometry and our imaging to be devoid of anything $>14M_J$ at $>15$ AU away and $>48M_J$ at separations of $<15$ AU. Given that $\sim 25\%$ of DAs have measurable metal lines and that these seem less likely to be due to interstellar medium accretion and more likely to be due to unseen companions, either substellar or planetary, they are interesting targets for faint companion searches (Zuckerman et al. 2003; Debes & Sigurdsson 2002).

Using a binomial-type distribution that has been used to calculate the frequency of brown dwarf companions to nearby stars, we can calculate limits to the frequency of substellar objects around DAZs, as well as our full sample of 20 WDs (McCarthy & Zuckerman 2004). That distribution is given by

$$P(f, d) = f^d (1-f)^{N-d} \frac{N!}{(N-d)!} d!,$$

where $P$ is the probability, $f$ the true frequency of objects, $N$ the number of observations, and $d$ the number of successful detections.

If one integrates over all the probabilities, one can derive limits that encompass $68\%$ of the distribution. From these limits we can compare our results with both the radial velocity surveys and imaging surveys for brown dwarfs. In this study we can place meaningful limits to planet and brown dwarf formation around stars that originally had masses between 1.5 and 7 $M_\odot$, the range of initial masses inferred for our targets. From our limit of $\sim 1^{\%}$ as the innermost separation at which we could detect a companion for all our targets, we can derive the innermost projected orbital separation that we probe. Since any companion that is found today in an orbit with semimajor axis $a$ had a primordial orbit $M_\star/M_\odot$ times smaller before the star lost its mass and turned into a WD, we can probe inward to regions that should have been sites for planet formation. With a subset of our targets sensitive to planetary-mass objects at separations that would be where planets with orbits similar to that of Jupiter would be found, we can study a region of parameter space complementary to radial velocity surveys (Marcy & Butler 2000). Since our observations are also sensitive to brown dwarfs, we also complement surveys for widely separated brown dwarf companions to WDs (Farihi et al. 2005).

For our samples we neglect WD 0501+527 and WD 1213+529, since the observations of these targets are significantly less sensitive than the other observations. Of the 18 remaining WDs from the DSW05b and CFHT samples, eight are DAZs, and the rest are a mixture of other WD spectral types, including DAs with no detectable metals in their atmospheres.

In our DAZ sample, which includes those objects observed in DSW05b, WD 1633+433, and WD 1213+528, the images of four WDs were sensitive enough to detect planets, and none were found. Therefore, they do not have planetary-mass objects $>10M_J$ at projected separations of $>21$ AU, corresponding to an inferred minimum primordial separation of $>6$ AU. When we integrate over all possible probabilities we get an inferred limit of $<20\%$ for the frequency of massive planets in orbit around DAZs. Assuming that every DAZ may possess a planetary system, this is within a factor of 4 of the frequency of massive planets discovered with the radial velocity surveys with $M$ sin $i$ $(>10M_J$, in which 6 of 118 discovered planetary systems$^6$ possess such companions at $<5-6$ AU, as well as radial velocity surveys of G giants (Marcy & Butler 2000; Sato et al. 2003). Furthermore, none of the eight apparently single DAZs showed the presence of companions $>70M_J$ in close, unresolved orbits. This implies that $<12\%$ of DAZs have companions that are stellar. Any unseen object that could pollute a WD would have to be substellar for the majority of current apparently single DAZs.

For our total sample of 18 WDs, we can also place limits on any object $>19M_J$ present at projected separations $>34$ AU and corresponding to a minimum primordial orbit of $>10$ AU. From zero detections in this sample, we infer that intermediate-mass stars between 1.5 and 7 $M_\odot$ have brown dwarf companions $<6\%$ of the time. Also, for our entire sample of nearby WDs, 7 of the 18 were sensitive enough to detect massive planets ($M > 10M_J$) at projected separations of $>21$ AU, with inferred primordial separations of $>6$ AU. Therefore, the upper limit for the presence of massive planets around intermediate-mass stars is $<13\%$. If we also include the results of a planet search among single WDs in the Hyades, we can effectively double our sample size of targets sensitive to massive planets (Friedrich et al. 2005). In the Friedrich et al. (2005) survey, they found no planets $>10M_J$ at separations $>23$ AU, corresponding to primordial separations of $>5$ AU. Combined with our results, the upper limit for massive planets around single WDs (at 68% confidence) is then closer to 7%.

High spatial resolution imaging of WDs will also be important for supporting observations for Spitzer observations of WDs that are looking for mid-IR excesses due to substellar companions. WD 1121-216 in particular may falsely show an excess due to it temporarily being coincident with a background galaxy. Approximately 100 WDs have been approved to be observed with Spitzer in the Cycle 1 General Observer programs. A combination of the Spitzer photometry and imaging would provide a more sensitive test for unresolved companions while providing a check against source confusion due to Spitzer’s larger PSF with IRAC, for example (Fazio et al. 2004). A large survey like that would also start placing rigorous limits on the presence of faint companions to nearby WDs.

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6 See http://www.obspm.fr/encycl/encycl.html.
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