A Spectroscopic Search for White Dwarf Companions to 101 Nearby M Dwarfs*

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Abstract

Recent studies of the stellar population in the solar neighborhood (<20 pc) suggest that there are undetected white dwarfs (WDs) in multiple systems with main-sequence companions. Detecting these hidden stars and obtaining a more complete census of nearby WDs is important for our understanding of stellar and galactic evolution, as well as the study of explosive phenomena. In an attempt to uncover these hidden WDs, we present intermediate resolution spectroscopy over the wavelength range of 3000–25000 Å of 101 nearby M dwarfs (dMs), observed with the Very Large Telescope X-Shooter spectrograph. For each star we search for a hot component superimposed on the dM spectrum. X-Shooter has excellent blue sensitivity and thus can reveal a faint hot WD despite the brightness of its red companion. Visual examination shows no clear evidence of a WD in any of the spectra. We place upper limits on the effective temperatures of WDs that may still be hiding by fitting dM templates to the spectra and modeling the WD spectra. On average our survey is sensitive to WDs hotter than about 5300 K. This suggests that the frequency of WD companions of $T_{\text{eff}} \gtrsim 5300$ K with separation of the order of $\lesssim 50$ au among the local dM population is $<3\%$ at the 95% confidence level. The reduced spectra are made available via the WISEREP³ repository.

Key words: binaries: general – stars: late-type – white dwarfs

Supporting material: figure set, machine-readable tables

1. Introduction

White dwarf (WD) stars are an important ingredient of stellar populations. As the end state of over 97% of stars (Fontaine et al. 2001), they play a crucial role in the understanding of stellar and galactic evolution. For example, relating the luminosity function of these stars to their cooling sequences can yield estimates of their age, and thus the age of the galactic disk and the universe (e.g., Winget & van Horn 1987; García-Berro & Oswalt 2016).

Characterizing WDs in binary and higher multiplicity systems is paramount for many fields of research such as the WD mass–radius relation (Provencal et al. 1998), the WD initial-to-final mass relation (Weidemann 2000), and also explosive phenomena. For example, the origin of SN Ia explosions is still unknown. There is evidence that WDs are the progenitors of these explosions (Nugent et al. 2011), but the trigger of the explosion is still a puzzle. The two common models suggest a WD accreting material from a main-sequence or red giant companion, or two binary WDs merging and exploding (see Howell 2011 and Maoz et al. 2014 for reviews). Both models struggle to ignite an explosive detonation in simulations (Dong et al. 2015). A different model suggests an explosion due to a collision of two WDs in a triple system (Katz & Dong 2012; Kushnir et al. 2013). This scenario easily produces explosions, but it is not clear whether enough systems such as these exist to account for the observed supernova rates. Improved statistics of WDs in multiple systems can constrain these models.

WDs are compact faint objects and are thus difficult to detect in multiple systems in which brighter, main-sequence

companions are present. Therefore, efforts have been made to obtain a complete census of WDs in the nearby solar neighborhood, from which statistics about galactic populations can be inferred. Holberg et al. made two such attempts for the local volume within 20 pc (Holberg et al. 2002, 2008) reaching an estimated completeness of 80%, suggesting there are still ~ 33 undetected WDs left in this volume. Further efforts including Sion et al. (2009), Giammichele et al. (2012), and Oswalt et al. (2016) have improved upon this, reaching an estimated 86% completeness. In contrast, Katz et al. (2014) claims that the completeness fraction of Holberg et al. (2008) is over-estimated and that the actual value is smaller.

So are there “missing” WDs? The answer may hide in multiple systems. According to Oswalt et al. (2016), in the local neighborhood 74% of WDs are single stars and only 26% are in binary or higher multiplicity systems. This is in contrast with the progenitors of these WDs—main-sequence stars of K type and earlier (up to the minimum mass for supernova)—which show multiplicity rates of $\sim 45\%$ and higher (e.g., Mason et al. 2009; Raghavan et al. 2010; De Rosa et al. 2014).

Ferrario (2012) suggests that this discrepancy may be due to an observational bias—WDs in binaries are simply too faint compared to their companions, and are thus not detected. Katz et al. (2014) provided observational evidence supporting this claim using a WD luminosity-cooling age relation to derive the theoretically expected distribution of absolute visual magnitudes. They showed that the observed single WDs in the 20 pc sample of Holberg et al. (2008) roughly follow this distribution, while the number of WDs in binaries drops compared to the expectation for magnitudes of 12 and fainter. This gap between expected and observed WDs in binaries implies that there are ~ 100 such nearby missing WDs, hiding in the light of main-sequence companions. This is a significant number, considering that the local 20 pc volume contains ~ 1900 non-WD stars in total.

* Based on observations collected in service mode using the Very Large Telescope (VLT) under program IDs 095_D-0949(A) and 096_D-0963(A).

³ <http://wiserep.weizmann.ac.il>

We present an attempt to unveil some of those WD companions by obtaining spectra of 101 nearby M dwarfs using the Very Large Telescope X-Shooter spectrograph. The targets were selected based on their strong near-UV (NUV) emission as measured by the *GALEX* survey (Martin et al. 2005), which may arise from the contribution of a hidden WD to the spectrum, or from magnetic activity of the dM. We attempt to detect WD companions by examining the spectra for characteristic features of WDs. As no such evidence of WD presence is visible, we then put upper limits on the effective temperatures of WDs that may still be hiding below our detection threshold.

This paper is organized as follows. In Section 2 we present the observations, the results and analysis are given in Section 3, and in Section 4 we discuss and summarize the main ideas.

2. Data

2.1. Target Selection

Our initial sample consists of dMs within 20 pc of the Sun, taken from the Gliese Catalog of Nearby Stars, 3rd edition (Gliese & Jahreiss 1995). We have selected dMs since earlier types would be too bright and blue to allow detection of a faint blue companion. We have limited our selection to dMs with absolute V magnitudes of 10–16 mag. The faint limit was set by the faintest single WD in both the Holberg et al. (2008) and Gliese catalogs. Thus, a WD companion to a dM fainter than that would have to be brighter than the dM companion and would dominate the spectrum. In that case, the star would not be classified as a dM in the first place. The bright limit was set to ensure that dwarf stars were selected and not sub-giants, as the Gliese catalog does not always include the luminosity class of the M stars. In addition, we have discarded targets that have nearby objects in the catalog with separations of less than $30''$. To increase our chances of detection, we cross-correlated our target list with the *GALEX* survey, choosing the targets that showed the strongest NUV emission, compared to their V magnitude ($NUV - V$ color). This emission can be caused by the contribution of a hidden WD companion to the blue side of the spectrum. Jones & West (2016) showed that dM-WD binaries tend to emit more NUV than single dMs, but also showed that this can also be the result of magnetic activity of dMs.

Cross matching between the Gliese and *GALEX* catalogs was done using tools in the astronomy & astrophysics package for Matlab (Ofek 2014). Figure 1 illustrates our color cut which left us with a total of 138 dMs.

2.2. Observations and Data Reduction

The observations were performed with the X-Shooter spectrograph (Vernet et al. 2011) mounted at the *Kueyen* unit of the Very Large Telescope (UT2), operated by the European Southern Observatory (ESO) on Cerro Paranal in Chile (Program IDs 095_D-0949(A) and 096_D-0963(A), PI: Paul Vreesswijk). The X-Shooter records spectra with three separate arms simultaneously—UVB, VIS, and NIR. This allows a wide wavelength range (3000–25000 Å) while maintaining good sensitivity throughout the range. In particular, the instrument is very blue-sensitive down to the atmospheric cutoff around 3000 Å. Thus, we benefit from the ability to characterize the dM spectrum in the red part while allowing possible detection of WD contribution in the blue part.

Figure 1. $V/NUV - V$ magnitude—color diagram of the stars in the Gliese catalog within 20 pc of the Sun. M stars are shown in red, single WDs (including additions from the Holberg et al. (2008) catalog) are shown in blue and other stars are shown in black. The purple line illustrates our color cut and the purple stars are the 138 M stars out of which our targets were selected.

Since our targets are very bright, our observation plan was submitted to the ESO as a “filler” program, to be executed during poor seeing conditions ($>1''.5$). We obtained service-mode observations with VLT/X-Shooter for 60 (41) targets during ESO Period 95 (96), securing spectra of a total of 101 dMs. Corrected locations of all targets were calculated using proper motions from the Stauffer et al. (2010) 2MASS-Gliese cross-correlation catalog. Exposure times were typically 120 s for UVB, 90 s for VIS, and four separate exposures of 30 s each for NIR. In some cases, exposure times were increased for faint targets or decreased to prevent saturation of the detector. Moreover, saturation was avoided for bright targets ($M_V \sim 10$) by using a 1×1 binning read-out mode instead of 1×2 . All of the observations were made in the Stare mode using the widest $5''.0$ slit, to increase the chances of including a WD companion in the spectrum (up to a separation of 40 au for a 16 pc target, the distance at half the 20 pc volume). The resolving power of the X-Shooter for the $5''.0$ slit was measured to be about 5000, 9000, and 5000 for the UVB, VIS, and NIR arms, respectively. This was done by examining several unresolved lines in the spectra and dividing their wavelengths by their full width at half maximum.

Spectra were reduced using the ESO’s Reflex pipeline version 2.8 (Freudling et al. 2013). Automatic telluric correction was performed by the pipeline. A built-in “optimal extraction” algorithm (Horne 1986) was used to increase the signal-to-noise ratio (S/N). For the UVB and VIS arms, optimal extraction yielded a mean improvement of 5% and 4% in SNR, respectively, compared to standard extraction. On the other hand, for the NIR arm a mean 4% decrease in SNR was noted, with artifacts introduced to some of the spectra. Thus, we have decided to use optimal extraction for the UVB and VIS arms only, and standard extraction for the NIR arm.

We removed very noisy parts in the UVB and VIS arms below 3200 and 5500 Å, respectively. The three spectral pieces were then stitched together using overlap regions as a reference. Both the UVB and the VIS spectra include a feature at ~ 5500 – 5800 Å due to the dichroic splitter of the X-Shooter (Chen et al. 2014). Thus, we excluded this feature from the overlap regions.

Figure 2. The M subclass distribution of the stars observed in this study.

The pipeline produces a flux-calibrated spectrum for each target using a spectroscopic standard star that was observed on the same night. This procedure assumes photometric nights. Therefore, we performed absolute calibration for each object using JHK band photometry from the 2MASS catalog (Skrutskie et al. 2006), since these are the only bands that are reported for all of our targets in the SIMBAD database (Wenger et al. 2000). We calculated JHK synthetic photometry for each spectrum and rescaled the flux to match the photometric data.

The log of spectroscopic observations is presented in Table 2 in the Appendix, along with plots of the reduced spectra. These are also available on the WISEREP⁴ repository (Yaron & Gal-Yam 2012) and are searchable via object name or by the type of “M dwarf.” The subclass distribution of our sample is presented in Figure 2.

3. Results and Analysis

3.1. Activity and Multiplicity

Out of the 101 observed targets, 65 of them show strong emission lines that are indicative of magnetic activity: the hydrogen Balmer series and the Ca II H and K lines (see Reid & Hawley 2005). An example of these lines for target GJ2069 is shown in Figure 3. The remainder of the targets show little or no emission lines. Five spectra are showing double emission lines (also shown in Figure 3), which suggests that these are in fact binary stars which are not listed in the Gliese catalog. A search of binary star catalogs (Mason et al. 2001 and Shkolnik et al. 2010) shows that these are indeed known binary or higher multiplicity systems, and revealed 21 additional multiples in our sample with separations smaller than half of our slit width (targets were positioned in the center of the slit) that were not filtered out initially. The separations of these systems are listed in Table 1 and we give special care to these in our analysis later on.

3.2. White Dwarf Spectral Features

According to the Kleinman et al. (2013) SDSS survey, over 90% of WDs are classified as having either hydrogen or helium

atmospheres, indicating a spectral type of DA or DB, respectively. Thus, we first visually examine the spectrum of each target in search of distinct broad absorption features typical of these spectroscopic classes. For type DA, these would be the hydrogen Balmer lines at 6563, 4861, 4341, and 3970 Å. For type DB, the dominant lines are from neutral helium at 4026, 4471, and 5875 Å (Bergeron et al. 2011). Some WDs show only a continuum spectrum—type DC. According to Giammichele et al. (2012), those can be hydrogen atmosphere WDs of $T_{\text{eff}} \leq 5000$ K or helium atmosphere WDs of $T_{\text{eff}} \leq 12,000$ K. The search for this type and other more exotic types was done by looking for a clear rise in the blue part of each target. No evidence for DA or DB features, nor of a clear blue rise, was found in any of the spectra.

3.3. Limits on the Temperature of Unseen WDs

Next, we place upper limits on the effective temperature of WDs that may still be hiding below our detection threshold. We do so by modeling spectra of WDs with a mass of $0.6 M_{\odot}$ as blackbodies of varying effective temperatures. We use this mass value as it is the peak of the narrow observed WD mass distribution (see Bergeron et al. 2001; Kepler et al. 2007). Using these models and spectral templates for each dM, we determine at which temperature the WD models can be rejected.

As spectral dM templates, we tried to use the Pickles (1998) spectral library, which did not provide good enough fits to our data due to the low resolution (~ 500 Å) and to a limited number of spectral subtypes. We have also tried using the PHOENIX synthetic spectral models (Husser et al. 2013), which did not describe our data well in the UVB and NIR parts. Eventually, we have decided to use our own data as templates, under the assumption that most of our targets do not hide WD companions. Indeed, the self-template method yields better fits for the vast majority of our targets (see Figure 6), compared with the alternative methods.

The best fitting template for each target was determined as the one with the lowest Residual Sum of Squares (RSS) score

$$\text{RSS} = \sum_i (f_{S,i} - f_{T,i})^2, \quad (1)$$

where $f_{S,i}$, $f_{T,i}$ are the flux values of the current target and of each template, respectively. Before calculating the RSS score, the spectra were rescaled to each other such that the flux integral is equal to one. We excluded from the fit the blue part below 6300 Å to minimize possible WD contamination, while keeping the prominent dM features that extend to redder wavelengths. We also excluded wavelength ranges of known telluric features at 6340–6420 Å, 6840–6960 Å, 7147–7323 Å, 7575–7705 Å, 8130–8365 Å, 8939–9240 Å, 9280–9830 Å, 10810–11710 Å, 12670–12710 Å, 13000–15030 Å, 17350–19810 Å, 19950–20350 Å, and 20480–20820 Å (Moehler et al. 2014). As we only have 101 spectra to work with, dividing them into magnetically active and non-active would limit our ability to find good templates. Thus, we included both active and non-active stars in the template bank for all targets while excluding the Balmer H α line from the fit range. As shown, for example, in Figure 6, nice fits are produced also when using active templates for non-active targets and vice versa.

⁴ <http://wiserep.weizmann.ac.il>

Figure 3. Example emission lines for GJ2069. The red lines indicate the first four Balmer series lines and the pink line indicate the Ca IIH/K lines. The double H α line is shown in the inset.

As WD synthetic spectra were not available to us, we chose to model WDs as blackbodies of varying effective temperatures and with radii that fit a typical mass of $0.6 M_{\odot}$. The radius for each T_{eff} value was calculated using $R^2 = GM/g$ and the surface gravity ($\log g$) values from the publicly available WD color model grids of Holberg & Bergeron (2006), Kowalski & Saumon (2006), Tremblay et al. (2011), and Bergeron et al. (2011). The absolute flux values of the models were calculated using these radii and the distance to each target, obtained from the Gliese catalog.

Next, we determine the hottest WD that may be hiding in the data for each target. The dM fits are not perfect and exhibit correlated residuals (i.e., spectral regions that are systematically lower or higher between each target and its template). Such correlated noise make it very difficult to make quantitative statements. We attempt to explain the observed spectrum using a combination of the template spectrum and an approximate WD model, and to ask when the temperature of the WD produces a “noticeable” effect on the composed spectrum. In each such fit, the WD flux is completely determined by its radius (assuming a $0.6 M_{\odot}$ WD), its distance, and assuming a blackbody emitter. Therefore, we use several methods to put limits on the WD temperature that can be hidden in each system. We note that since the WD luminosity is very sensitive to its effective temperature (i.e., $\propto T_{\text{eff}}^4$), any reasonable estimator will yield similar results regardless of the details of the test. In the first method, we reject WD models that yield an RSS score double than that of the template alone. We add the flux of the best fit template to the blackbody models for a grid of effective temperatures between 1500 and 20,000 K, and calculate the RSS score for each temperature. We then compare these scores with the RSS of the fit with no WD. The lowest temperature for which the RSS score is more than double the score without the model is set as our upper limit. This test is arbitrary, but due to the extreme sensitivity of the luminosity on T_{eff} , the obtained limits are similar for different criteria. For

example, changing the threshold to three times the RSS yields an average increase in the limit temperature of only 400 K. Our temperature grid follows that of the color models—from 1500 to 5500 K in steps of 250 K and then to 15,000 K in steps of 500 K. As opposed to the template fitting, we now calculate the RSS score for wavelengths 3200–10000 Å, where WD contribution would be dominant. In addition to the H α line and tellurics, we also remove from the fit range the rest of the Balmer emission lines, the Ca II lines, and the X-Shooter dichroic feature.

In the second method, we reject WD models that exceed the fit residuals envelope. The envelope is defined as the 99th percentile of the flux for the absolute value of the fit residuals. In this case, the limit is set as the lowest temperature for which the blackbody model flux exceeds the envelope. In other words, the rejected WD model is the coldest one, which is not consistent with the residuals of the fit.

The third method is robust and template-independent. Here, we compare the integrated flux of the very blue part of the dM spectra to that of our blackbody models. The limit is set as the temperature of the coldest model for which the total blue flux is greater than that of the dM. This was done for wavelengths of 3200–3700 Å, as this range features only a weak continuum from the dMs. In addition, this range is bluer than that of the Balmer series, thus avoiding the typical absorption features of WDs and ensuring that blackbody is a good approximation for WD spectra. An example of the three methods is given in Figure 4.

To verify that the blackbody model describes WDs well enough for our purposes, we repeat the analysis using explicit WD models from Koester (2010). Since the publicly available spectra⁵ range from $T_{\text{eff}} \geq 6000$ K, we performed the analysis on a sample of targets, which yielded higher limits than this

⁵ <http://svo2.cab.inta-csic.es/theory/newov/index.php?model=koester>

Table 1
Obtained Results of Spectral Analysis

Name	Template	RSS (K)	Env. (K)	Blue Flux (K)	Act. ^a	Sep. ^b ($''$)
NN3010	...	...	...	5250	V	0.1
NN3017	GJ2021	5250	6500	5250	V	...
NN3027	NN3682	5250	6500	5500	V	...
NN3033	NN3518	5000	6500	4750	V	...
NN3034	GJ1204	5000	6500	5000	...	...
NN3039	...	...	...	6000	V	0.7
GJ1019	NN3227	6000	6000	5000	...	...
NN3056	NN3142	4500	6000	5250	...	...
GJ1024	GJ1031	6000	7000	5500	...	...
GJ1029	NN3937	4750	6000	3750	...	...
GJ1031	NN3225	5000	5500	5250	V	...
GJ2021	GJ1031	4500	5500	4750	...	...
NN3076	...	...	...	4250	V	0.3
NN3119	NN4292	4000	5000	4250	V	...
GI83.1	NN3225	4000	5000	4750	V	...
NN3129	...	...	...	5500	D ^c	...
NN3142	NN3149	5250	7000	5500	V	...
NN3143	GI828	6000	6500	5500	V	...
NN3149	GJ1031	6000	7000	6500	V	...
NN3148	GJ1284	6500	8000	6500	V	...
GI102	GJ1031	5250	6500	5250	...	...
GJ1055	NN3253	3750	5000	4250	...	...
NN3224	...	...	...	4500	D	0.3+2
NN3225	GI83.1	4500	5250	4000	V	...
NN3227	GI729	7500	7000	6000	V	...
NN3237	NN3253	6500	6500	5500	V	...
NN3253	NN3237	4500	5500	4500	...	...
NN3261	...	...	...	6500	V	0.8
NN3296	NN3225	5500	6000	5000	V	...
NN3304	...	...	...	5500	V	1.1
NN3322	...	...	...	6500	V	1.4
NN3326	NN3967	6000	6500	5250	V	...
NN3332	...	...	...	8000	V	0.8
NN3344	GI207.1	10000	9500	8500	...	...
GI207.1	GJ1284	10500	9500	8000	V	...
GJ1083	...	...	...	4000	V	0.5
NN3405	GI828	6500	7500	6000	...	...
GJ1093	GJ1286	4000	5250	3750	...	...
NN3423	GI729	5500	6500	5500	V	...
GJ1096	NN3225	5000	6000	4500	V	...
GI268.3	...	...	...	6500	...	0.1
NN3454	...	...	...	4750	V	0.3
NN3463	GJ1103	4250	5250	4750	...	...
GJ1103	NN3463	5500	5500	5000	...	...
NN3466	...	...	...	5500	...	1
GJ1108	...	...	...	7500	D	0.3+14
GI300	...	...	...	5250	...	2
NN3503	NN3518	4500	5500	4250	...	...
GJ2069	...	...	...	7000	D	1+10+22
GI324	NN3967	6500	7000	5500	...	...
NN3518	NN3033	5000	6000	5000	V	...
GJ1116	...	...	...	3750	V	1.8
NN3543	NN3344	8500	8000	6500	Ca	...
NN3549	NN3937	4000	5250	4250	V	...
GI347	GJ1031	5250	6000	4500	...	...
GI359	GI347	4500	6000	4500	...	...
NN3571	GI347	4750	6000	4750	V	...
NN3572	GJ1186	8500	8000	6500	...	...
NN3573	NN3571	7000	7500	5000	...	...
NN3590	GJ1186	6000	7500	5000	...	...
NN3647	GJ1031	6000	8000	6500	...	...
NN3654	GI781.1	7000	7500	5500	...	...
NN3657	GJ1031	4250	6000	4250	...	...

Table 1
(Continued)

Name	Template	RSS (K)	Env. (K)	Blue Flux (K)	Act. ^a	Sep. ^b ($''$)
NN3668	NN3463	4500	6000	4750	...	...
NN3682	NN3780	6000	6500	6000	V	...
NN3685	NN3149	6500	7000	6000	V	...
GJ1154	NN3149	4250	5500	4750	V	...
NN3780	NN3682	6000	6500	6000	V	...
GJ1179	NN3682	4750	5250	3750	V	...
NN3808	GJ2021	6000	6500	5000	V	...
GI540.2	NN4292	5500	6500	5250	V	...
NN3856	NN3780	5250	6500	5500	V	...
GJ1186	NN4292	5250	5500	4500	...	...
NN3900	GI828	5500	7000	6000	...	...
NN3937	GJ1029	4750	5500	4250	...	...
GJ1204	GJ1284	6000	6500	5250	V	...
NN3967	NN3326	4500	6000	5000	V	...
NN3981	...	...	...	5500	V	0.6
GJ1210	...	...	...	4750	V	0.4
NN4032	NN3227	8500	8000	6500	...	...
NN4071	NN3423	6000	7000	5500	V	...
GI729	NN3227	4750	6000	5250	V	...
GI781.1	NN4279	7500	8000	7000	V	...
GI791.2	...	...	...	5000	V	0+0.2
GI828	NN3143	4750	6500	5500	...	...
NN4201	...	...	...	5500	V	0.8
GI836	NN4071	6000	6500	6000	...	...
NN4215	NN4292	4500	5500	4500	...	...
NN4231	...	...	...	7500	V	0.2+0.7
NN4239	NN3657	5250	6000	4500	...	...
NN4274	GJ1154	4750	5250	4750	V	...
NN4279	GI781.1	5000	6000	5500	V	...
NN4282	...	...	...	7500	V	1.5
NN4292	NN3119	5500	5500	4500	V	...
NN4302	GI781.1	6000	6500	5500	...	...
NN4326	...	...	...	6500	V	0.1
GJ1284	GI83.1	9500	9000	7500	V	...
GJ1286	GI207.1	5000	5250	4000	...	...
NN4360	...	...	...	4500	V	0.6
NN4362	GJ1284	7500	8000	7000	V	...
NN4378	...	...	...	7000	D	0.6+20

Notes. RSS, envelope, and blue flux are the limits obtained using the three methods. Targets without reported templates and RSS/envelope limits are those defined as close binaries.

^a Activity—B+Ca stands for Balmer and Ca II emission lines, Ca for Ca II lines only, D for double emission lines (Balmer and Ca II).

^b Companion separations from the WDS catalog, listed for targets where at least one companion is closer than $2''5$.

^c Listed as binary in Shkolnik et al. (2010), no separation reported.

(This table is available in machine-readable form.)

temperature and found consistent results to within 500 K, lending support to the use of the simple blackbody model.

As noted before, 26 of our targets are listed in binary catalogs as binaries or higher multiplicity systems with separations of less than $2''5$ (close binaries, hereafter), which is within half the X-Shooter slit width that we have used. Five of those display double emission lines in their spectra. The spectra of the rest of these close binaries may or may not contain more than one star. Thus, they are problematic for our limit analysis and must be analyzed with care. As a first precaution, we have taken these targets out of the template

Figure 4. Example of the limit calculations for NN4274. Top panel: the blue part of the spectrum is shown in black. The rejected blackbody model from the blue flux method is shown in orange. The 3700 Å line defining the blue flux region is shown in green. Bottom panel: the fit residuals from the best fit template GJ1154 are shown in black. In orange and blue are the rejected blackbody models from the RSS and envelope methods, respectively. The 99% flux envelope is shown in green.

Figure 5. The effective temperature distributions of the limits derived in this study and of the WDs in the Holberg et al. (2008) catalog.

bank. Second, for these cases we only report the limits obtained using the blue flux method, which is independent of template.

The limits obtained and best fit templates for each target are listed in Table 1. The figure set for Figure 6 displays, for each target,

1. the spectrum,
2. the best fit template, rescaled to the flux of the target and
3. the residuals of the fit and the rejected blackbody models used to derive the limits.

The figure set for Figure 7 displays the spectra of the close binary targets, for which no template analysis was performed.

4. Discussion

Motivated by the evidence for missing WDs in multiple systems, we have used the X-Shooter to record spectra of 101 dMs that show strong NUV emission. We have examined these spectra for evidence of WD spectral features. When those were not found, we have used the spectra themselves as templates, modeled WDs as blackbodies, and obtained upper limits for the effective temperatures of WDs that may still be hidden, using three different methods. It is important to note that the limits obtained are only within our slit width of 5". Since our targets are positioned roughly at the center of the slit, this corresponds to a companion at 40 au for a target at 16 pc (the distance at half

Figure 6. Example spectral fitting for GJ1031. The spectrum (top panel), the best fit template, rescaled to the flux of the target (middle panel), and the residuals of the fit and the rejected blackbody models used to derive the limits (bottom panel). The excluded fit ranges of tellurics, emission lines, and dichroic feature are colored in gray.

(The complete figure set (75 images) is available.)

the 20 pc volume). Though our slit is only 5'' wide, it is 11'' long, which could allow a companion at larger separations. Thus, we take the order of ~ 50 au as our typical separation limit.

Figure 5 shows the effective temperature distribution of our derived limits, selected as the tightest limit for each target among the three methods. Also shown is the effective temperature distribution of WDs in the Holberg et al. (2008) catalog. According to these, our limit analysis is sensitive to $\sim 75\%$ of WDs in the local volume. The average obtained limit for our 101 dM sample is 5300 K. Thus, the frequency of dM-WD binaries with WDs hotter than that is smaller than 3% at the 95% confidence level.

The Gliese catalog lists ~ 1900 non-WD stars with distances below 20 pc. Assuming that 100 WD companions are missing from that volume (Katz et al. 2014) and that WDs do not prefer specific class of companions, then 5% of the stars should have WD companions. As we have detected no WDs in our 101 dM sample, this hypothesis can be rejected at the 99.3% confidence level. However, our survey is sensitive to WDs hotter than ~ 5300 K, corresponding to $\sim 75\%$ of the known local population. In addition, our slit width limits our survey to separations of the order of $\lesssim 50$ au, which corresponds to 55% of dM-WD pairs (Farihi et al. 2010). Taking both into account, the expectancy is to detect only two WDs in our sample, and this hypothesis can be rejected at the 86% confidence level. The missing WDs may be colder than our detection limit or outside our slit, thus undetected. Another possibility is that the missing WDs are not hidden in the shadow of dMs, but rather are companions to stars of earlier types, as proposed in Ferrario (2012). Or else, perhaps not as many WDs are missing from the local volume as claimed.

It is interesting to note that selecting targets according to NUV emission produced a strong bias toward active dMs. For example, for spectral types M4 and M5, which make up the majority of our sample, we noted a 62% activity fraction, as opposed to $\sim 35\%$ for the SDSS survey of West et al. (2004). Studies of magnetic activity of dMs can thus benefit from our data set.

As mentioned before, our spectra are available online for public use. In our observations, we covered the entire wavelength range of active and non-active dMs at medium resolution, including several binaries with resolved double emission lines. We hope that this data will be useful for future research.

We would like to thank Barak Zackay for many insightful discussions. This work used the astronomy & astrophysics package for Matlab (Ofek 2014), the SIMBAD database, operated at CDS, Strasbourg, France, and used data obtained from the Weizmann interactive supernova data repository (<http://wiserep.weizmann.ac.il>). This work also made use of the data products from the 2MASS, which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by NASA and the NSF. This work has made use of the Washington Double Star Catalog maintained at the U.S. Naval Observatory, made use of the tables for evolutionary sequences of WD atmospheres of Holberg & Bergeron (2006), Kowalski & Saumon (2006), Tremblay et al. (2011), and Bergeron et al. (2011; <http://www.astro.umontreal.ca/~bergeron/CoolingModels/>), and made use of the observations made with the NASA *Galaxy Evolution Explorer*. GALEX is operated for NASA by the California Institute of Technology under NASA contract NAS5-98034. We acknowledge support from the Weizmann Institute, in particular the Kimmel Award.

Appendix

The appendix contains Table 2 of the observation log, Figure 6, which contains the spectra, the best fit templates, the fit residuals, and blackbody models of the derived limits. Excluded fit ranges of tellurics, emission lines, and dichroic feature are colored in gray. Also included is Figure 7, which displays the spectra of the close binary targets.

Table 2
Observed M dwarfs

Name	R.A.	Decl.	Spectral Type	M_V	Distance (pc)	Observation Date	Observation UT Time	Airmass	Seeing (")	UVB Exposure (s)	VIS Exposure (s)	NIR Exposure (s)
NN3010	00:08:53.95	+20:50:22.4	M5	13.54	10.64	2015 Jul 16	09:54:56	1.452	0.9	120	90	4 × 30
NN3017	00:15:36.88	−29:46:02.7	M4	14.31	17.86	2015 Aug 13	05:25:54	1.138	1.5	120	90	4 × 30
NN3027	00:18:54.11	+27:48:47.4	M4	13.86	19.23	2015 Oct 30	00:41:26	1.914	1.2	120	90	4 × 30
NN3033	00:24:35.78	+30:02:30.2	M5	14.54	18.87	2015 Oct 30	01:03:07	1.937	1.1	120	90	4 × 30
NN3034	00:25:20.42	+22:53:04.0	M4	14.30	18.87	2015 Jun 20	10:06:16	1.566	1.1	120	90	4 × 30
NN3039	00:32:34.97	+07:29:25.3	M4	12.70	11.63	2015 Jul 25	08:58:25	1.182	1.1	120	90	4 × 30
GJ1019	00:43:35.52	+26:28:25.1	M4	14.52	19.27	2015 Oct 14	05:33:38	1.886	1.1	120	90	4 × 30
NN3056	00:47:08.22	−23:30:31.1	M3	14.40	18.52	2015 Aug 13	05:47:17	1.169	1.6	120	90	4 × 30
GJ1024	00:56:39.19	+17:27:30.3	M4	13.71	17.42	2015 Jul 25	08:49:12	1.371	1.1	120	90	4 × 30
GJ1029	01:05:39.95	+28:29:31.3	M5	14.80	12.56	2015 Oct 14	06:01:32	1.919	1.2	120	90	4 × 30
GJ1031	01:08:19.12	−28:48:23.6	M3	13.42	13.16	2015 Aug 13	05:33:08	1.277	1.2	120	90	4 × 30
GJ2021	01:09:19.02	−24:30:28.3	M4	14.52	15.38	2015 Aug 13	05:40:14	1.262	1.3	120	90	4 × 30
NN3076	01:11:25.65	+15:26:18.5	M5	14.36	8.47	2015 Jul 25	07:50:46	1.510	1.2	120	90	4 × 30
NN3119	01:51:04.76	−06:07:10.0	M4.5	14.60	10.00	2015 Jul 25	09:23:14	1.089	1.0	120	90	4 × 30
Gl83.1	02:00:14.15	+13:02:38.3	M4	12.28	4.47	2015 Jul 25	08:03:38	1.631	1.2	120	90	4 × 30
NN3129	02:02:44.89	+13:34:30.9	M4.5	14.27	17.24	2015 Jul 25	08:19:09	1.570	1.2	120	90	4 × 30
NN3142	02:12:55.31	+00:00:17.3	M4	13.50	16.67	2015 Jul 25	09:33:35	1.155	0.9	120	90	4 × 30
NN3143	02:15:34.75	+33:57:34.9	M3.5	13.58	17.24	2015 Oct 13	05:53:42	1.929	1.0	120	90	4 × 30
NN3149	02:16:35.90	−30:58:05.4	M4	13.00	11.36	2015 Aug 13	06:10:58	1.409	1.0	120	90	4 × 30
NN3148	02:16:41.99	−30:59:15.8	M3	12.00	11.36	2015 Aug 13	06:03:07	1.453	1.0	120	90	4 × 30
Gl102	02:33:37.24	+24:55:27.3	M3.5	12.96	9.77	2015 Jul 25	09:50:28	1.651	0.8	120	90	4 × 30
GJ1055	03:09:00.59	+10:01:16.4	M5	14.85	11.88	2015 Dec 15	04:41:59	1.536	0.8	120	90	4 × 30
NN3224	03:25:42.18	+05:51:50.4	M4.5	14.70	12.99	2015 Dec 15	04:50:56	1.417	0.8	120	90	4 × 30
NN3225	03:26:45.08	+19:14:39.3	M4.5	14.96	16.67	2015 Oct 11	09:23:10	1.855	1.0	120	90	4 × 30
NN3227	03:28:49.89	+26:29:10.3	M4	13.40	18.18	2015 Oct 11	08:01:56	1.689	0.4	120	90	4 × 30
NN3237	03:36:41.04	+03:29:17.5	M5	13.86	14.29	2015 Dec 15	04:59:38	1.369	0.8	120	90	4 × 30
NN3253	03:52:42.29	+17:00:55.0	M5	13.70	9.62	2015 Oct 14	06:27:09	1.360	0.8	120	90	4 × 30
NN3261	04:05:38.91	+05:44:40.3	M3.5	12.89	15.87	2015 Dec 15	05:07:15	1.325	0.8	120	90	4 × 30
NN3296	04:33:34.62	+20:44:41.7	M5	14.60	15.63	2015 Oct 14	07:22:20	1.432	1.2	120	90	4 × 30
NN3304	04:38:13.13	+28:12:58.7	M4.5	12.53	10.00	2015 Oct 13	07:31:23	1.665	1.0	120	90	4 × 30
NN3322	05:01:58.86	+09:58:57.7	M3.5	11.47	7.04	2015 Dec 17	05:47:09	1.367	0.7	120	90	4 × 30
NN3326	05:04:14.67	+11:03:27.3	M5	13.75	13.70	2015 Dec 17	05:58:45	1.419	0.6	120	90	4 × 30
NN3332	05:06:49.54	−21:35:04.8	M3	11.66	12.05	2015 Oct 21	06:26:10	1.063	1.1	60	45	4 × 15
NN3344	05:16:00.36	−72:13:59.7	M2	11.70	19.23	2015 Oct 21	06:35:03	1.523	0.8	120	90	4 × 30
Gl207.1	05:33:44.55	+01:56:39.5	M3	11.53	15.08	2015 Dec 17	05:37:45	1.163	0.6	60	45	4 × 10
GJ1083	05:40:25.91	+24:48:02.3	M7	14.85	10.34	2015 Oct 11	08:28:00	1.560	1.3	120	90	4 × 30
NN3405	06:42:13.46	+03:35:26.5	M4	13.33	15.63	2015 Dec 17	06:29:22	1.159	0.7	120	90	4 × 30
GJ1093	06:59:29.95	+19:20:41.0	M5	14.83	7.76	2015 Oct 11	08:48:44	1.542	1.0	120	90	4 × 30
NN3423	07:03:23.25	+34:41:54.9	M4	13.17	13.33	2015 Nov 06	08:31:36	1.957	1.1	120	90	4 × 30
GJ1096	07:16:18.07	+33:09:03.8	M5	14.48	14.90	2015 Nov 07	08:40:59	1.873	1.1	120	90	4 × 30
Gl268.3	07:16:19.93	+27:08:29.8	M3	10.85	7.94	2015 Oct 11	08:59:03	1.842	0.8	120	90	4 × 10
NN3454	07:36:25.38	+07:04:38.6	M4.5	13.22	6.17	2015 Dec 17	06:37:36	1.174	0.6	120	90	4 × 30
NN3463	07:51:51.87	+05:32:51.1	M4.5	14.75	15.92	2015 Dec 07	07:59:18	1.165	0.7	120	90	4 × 30
GJ1103	07:51:54.99	−00:00:23.2	M4.5	13.50	8.79	2015 Dec 07	08:26:09	1.132	0.8	120	90	4 × 30
NN3466	07:54:55.22	−29:21:04.4	M4	13.38	12.50	2015 Oct 21	07:08:15	1.462	0.8	120	90	4 × 30
GJ1108	08:08:55.43	+32:49:02.6	M2.8+M3.3	12.12	17.24	2015 Dec 06	08:05:23	1.855	0.9	120	90	4 × 20
Gl300	08:12:40.98	−21:33:18.1	M3.5	12.10	5.88	2015 Oct 21	06:57:12	1.734	0.7	120	90	4 × 30

Table 2
(Continued)

Name	R.A.	Decl.	Spectral Type	M_V	Distance (pc)	Observation Date	Observation UT Time	Airmass	Seeing (")	UVB Exposure (s)	VIS Exposure (s)	NIR Exposure (s)
NN3503	08:31:22.82	-10:29:59.9	M4	15.00	15.38	2015 Oct 21	07:25:13	1.802	1.1	120	90	4 × 30
GJ2069	08:31:37.48	+19:23:37.5	M5	11.89	8.77	2015 Nov 19	07:33:41	1.596	1.0	120	90	4 × 30
GI324	08:52:40.41	+28:18:55.5	M4	13.14	13.09	2015 Dec 09	07:47:06	1.683	0.8	120	90	4 × 30
NN3518	08:55:19.62	-23:52:14.1	M4	14.00	12.20	2015 Oct 21	07:32:49	1.776	0.9	120	90	4 × 30
GJ1116	08:58:14.39	+19:45:46.1	M5.5	14.06	5.23	2015 Nov 19	07:14:53	1.883	1.0	120	90	4 × 30
NN3543	09:16:20.35	-18:37:31.3	M2	10.75	12.50	2015 Apr 15	00:09:21	1.008	0.5	120	70	4 × 10
NN3549	09:18:41.36	+26:45:46.4	M5	16.00	20.00	2015 Dec 09	08:12:52	1.625	1.0	120	90	4 × 30
GI347	09:28:55.54	-07:22:22.0	M4.5	15.00	16.72	2015 May 19	01:03:31	1.332	1.2	120	90	4 × 30
GI359	09:41:02.70	+22:01:21.0	M4.5	14.23	12.17	2015 Apr 09	23:55:43	1.557	0.8	120	90	4 × 30
NN3571	09:53:54.82	+20:56:52.2	M4	14.05	10.20	2015 Apr 14	23:41:40	1.548	0.4	120	90	4 × 30
NN3572	09:55:43.61	+35:21:41.7	M3.5	12.73	17.54	2016 Feb 04	07:13:20	2.241	0.8	120	90	4 × 30
NN3573	09:56:26.53	+22:38:57.9	M4	14.20	16.13	2015 Apr 12	01:24:52	1.470	0.7	120	90	4 × 30
NN3590	10:15:06.93	+31:25:08.7	M4	13.60	18.18	2015 Dec 14	08:15:25	1.909	0.7	120	90	4 × 30
NN3647	11:11:51.74	+32:33:11.4	M3.5	12.38	12.20	2016 Feb 03	08:53:00	2.250	0.8	120	90	4 × 30
NN3654	11:16:37.08	-27:57:30.5	M3.5	13.70	15.63	2015 May 17	02:22:37	1.126	0.9	120	90	4 × 30
NN3657	11:23:07.96	+25:53:36.8	M5	15.14	17.33	2016 Feb 05	05:55:29	1.668	0.8	120	90	4 × 30
NN3668	11:31:08.78	-14:57:41.2	M5	14.29	12.82	2015 Jul 15	23:42:57	1.388	0.7	120	90	4 × 30
NN3682	11:43:23.43	+25:18:13.5	M4	13.83	18.87	2015 May 19	00:52:43	1.551	1.1	120	90	4 × 30
NN3685	11:47:40.46	+00:15:19.7	M4	13.25	15.63	2015 Jul 15	23:50:34	1.520	0.9	120	90	4 × 30
GJ1154	12:14:15.60	+00:37:22.9	M4.5	13.73	8.46	2015 Jul 16	00:00:32	1.431	1.0	120	90	4 × 30
NN3780	13:23:37.34	-25:54:47.8	M3.5	12.90	12.66	2015 Aug 10	23:35:04	1.256	1.2	120	90	4 × 30
GJ1179	13:48:11.82	+23:36:50.9	M5	15.32	11.99	2015 Jul 16	00:08:44	1.595	0.9	120	90	4 × 30
NN3808	13:48:48.66	+04:06:00.9	M4	14.34	16.39	2015 Aug 13	23:26:41	1.417	1.3	120	90	4 × 30
GI540.2	14:13:04.24	-12:01:31.5	M5	13.86	11.63	2015 Aug 13	23:36:29	1.192	0.9	120	90	4 × 30
NN3856	14:32:11.01	+16:00:49.1	M5	13.61	14.93	2015 Apr 21	06:55:55	1.465	0.8	120	90	4 × 30
GJ1186	14:53:37.31	+11:34:02.2	M4.5	15.29	18.55	2015 Apr 21	07:42:35	1.463	0.9	120	90	4 × 30
NN3900	15:19:11.00	-12:45:08.2	M4	12.58	13.33	2015 Jun 12	03:50:18	1.065	0.9	120	90	4 × 30
NN3937	16:04:20.00	-06:16:57.8	M4.5	15.51	16.56	2015 Apr 21	08:12:07	1.120	0.7	120	90	4 × 30
GJ1204	16:36:05.18	+08:48:47.7	M4	13.80	15.34	2015 Jun 12	04:52:04	1.234	0.8	120	90	4 × 30
NN3967	16:40:06.23	+00:42:16.9	M5	13.69	11.20	2015 Jun 12	04:09:01	1.106	0.8	120	90	4 × 30
NN3981	16:58:24.94	+13:58:11.5	M4	13.13	12.99	2015 Apr 02	09:25:52	1.288	0.8	120	90	4 × 30
GJ1210	17:07:40.42	+07:22:01.7	M5	14.01	12.82	2015 Jun 12	05:02:54	1.192	0.7	120	90	4 × 30
NN4032	17:53:00.42	+16:54:59.3	M3.5	12.69	17.54	2015 Apr 21	07:20:12	1.432	0.9	120	90	4 × 30
NN4071	18:42:45.07	+13:54:22.0	M5	12.81	10.42	2015 Apr 21	07:32:02	1.491	0.8	120	90	4 × 30
GI729	18:49:50.13	-23:50:14.4	M3.5	10.46	2.93	2015 Jun 12	04:42:07	1.067	0.8	120	30	4 × 10
GI781.1	20:07:45.27	-31:45:24.9	M4	12.50	19.72	2015 Jun 17	10:09:34	1.307	0.8	120	90	4 × 30
GI791.2	20:29:49.07	+09:41:23.1	M4.5	13.05	8.76	2015 Jun 17	09:44:17	1.473	0.6	120	90	4 × 30
GI828	21:26:53.22	-44:48:44.6	M3.5	14.10	14.93	2015 Jul 13	04:56:12	1.155	1.1	360	300	4 × 100
NN4201	21:32:22.36	+24:33:42.0	M4	12.66	12.35	2015 May 28	09:50:41	1.530	0.3	120	90	4 × 30
GI836	21:39:02.08	-24:09:40.8	M4	13.43	13.95	2015 Jul 13	05:11:28	1.097	0.8	360	300	4 × 60
NN4215	21:44:08.31	+17:04:38.2	M4.5	14.81	17.54	2015 Jun 15	09:49:04	1.387	0.9	120	90	4 × 30
NN4231	21:52:10.59	+05:37:33.7	M2.4	12.11	15.63	2015 May 22	09:38:37	1.197	0.8	120	90	4 × 30
NN4239	21:56:56.63	-01:54:00.5	M5	14.64	13.33	2015 Jul 13	04:38:48	1.397	1.1	360	300	4 × 100
NN4274	22:23:07.34	-17:36:36.2	M4.5	13.25	7.46	2015 Sep 09	04:51:51	1.036	0.9	120	90	4 × 30
NN4279	22:27:03.07	+06:49:33.4	M3.5	13.22	13.89	2015 Sep 09	05:01:00	1.222	1.0	120	90	4 × 30
NN4282	22:33:22.92	-09:36:53.0	M3	12.41	16.95	2015 Sep 09	05:09:45	1.076	0.8	120	90	4 × 30
NN4292	22:43:23.71	+22:08:17.8	M5	15.00	15.87	2015 Jul 25	07:26:48	1.463	1.3	120	90	4 × 30

Table 2
(Continued)

Name	R.A.	Decl.	Spectral Type	M_V	Distance (pc)	Observation Date	Observation UT Time	Airmass	Seeing ($''$)	UVB Exposure (s)	VIS Exposure (s)	NIR Exposure (s)
NN4302	22:54:47.15	−05:28:19.8	M4	13.90	20.00	2015 Aug 21	08:55:18	1.574	0.8	120	90	4×30
NN4326	23:17:28.57	+19:36:46.2	M2	12.10	12.82	2015 Jul 25	08:39:29	1.438	1.1	120	90	4×30
GJ1284	23:30:13.82	−20:23:29.3	M2	11.16	10.87	2015 Sep 09	05:36:07	1.013	0.8	100	75	4×15
GJ1286	23:35:11.31	−02:23:33.4	M5	14.69	7.22	2015 Sep 09	05:47:55	1.099	0.7	120	90	4×30
NN4360	23:45:30.87	−16:10:27.5	M5	14.50	9.01	2015 Sep 09	05:56:39	1.025	0.6	120	90	4×30
NN4362	23:48:35.42	−27:39:44.4	M2.5	12.40	18.87	2015 Aug 13	05:54:23	1.042	1.3	120	90	4×30
NN4378	23:57:20.84	−12:58:47.4	M4	12.93	17.86	2015 Sep 09	06:07:33	1.035	0.6	120	90	4×30

Note. Observed M dwarfs, ordered by R.A. spectral types are from SIMBAD (Wenger et al. 2000). The distances are from the Gliese catalog.

(This table is available in machine-readable form.)

Figure 7. Example of the spectrum of close binary NN3010.

(The complete figure set (26 images) is available.)

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