PHYSICAL PROPERTIES OF THE CURRENT CENSUS OF NORTHERN WHITE DWARFS WITHIN 40 pc OF THE SUN

M.-M. Limoges1,4, P. Bergeron1, and S. Lépine2,3

1 Département de Physique, Université de Montréal, C.P. 6128, Succ. Centre-Ville, Montréal, Québec H3C 3J7, Canada; limoges@astro.umontreal.ca, bergeron@astro.umontreal.ca
2 Department of Physics and Astronomy, Georgia State University, Atlanta, GA 30302-4106, USA; slepine@chara.gsu.edu
3 Department of Astrophysics, American Museum of Natural History, New York, NY 10024, USA

Received 2015 January 23; accepted 2015 May 8; published 2015 July 30

ABSTRACT

We present a detailed description of the physical properties of our current census of white dwarfs within 40 pc of the Sun, based on an exhaustive spectroscopic survey of northern hemisphere candidates from the SUPERBLINK proper motion database. Our method for selecting white dwarf candidates is based on a combination of theoretical color–magnitude relations and reduced proper motion diagrams. We reported in an earlier publication the discovery of nearly 200 new white dwarfs, and we present here the discovery of an additional 133 new white dwarfs, among which we identify 96 DA, 3 DB, 24 DC, 3 DQ, and 7 DZ stars. We further identify 178 white dwarfs that lie within 40 pc of the Sun, representing a 40% increase of the current census, which now includes 492 objects. We estimate the completeness of our survey at between 66% and 78%, allowing for uncertainties in the distance estimates. We also perform a homogeneous model atmosphere analysis of this 40 pc sample and find a large fraction of massive white dwarfs, indicating that we are successfully recovering the more massive, and less luminous objects often missed in other surveys. We also show that the 40 pc sample is dominated by cool and old white dwarfs, which populate the faint end of the luminosity function, although trigonometric parallaxes will be needed to shape this part of the luminosity function more accurately. Finally, we identify 4 probable members of the 20 pc sample, 4 suspected double degenerate binaries, and we also report the discovery of two new ZZ Ceti pulsators.

Key words: solar neighborhood – stars: distances – stars: fundamental parameters – stars: luminosity function, mass function – surveys – white dwarfs

Supporting material: extended figures, machine-readable tables

1. INTRODUCTION

The determination of the atmospheric parameters of individual white dwarf stars—effective temperature ($T_{\text{eff}}$), surface gravity ($\log g$), and atmospheric composition—has now reached an unprecedented level of accuracy, thanks to significant progress on both the observational and theoretical fronts. On the observational side, large samples of high signal-to-noise ratio (S/N) optical spectra can now be routinely obtained and analyzed using the so-called spectroscopic technique where observed line profiles are compared to the predictions of model atmospheres (see, e.g., Bergeron et al. 1992), reaching a precision as high as 1.2% in $T_{\text{eff}}$ measurements and 0.038 dex in $\log g$ for the DA stars (Liebert et al. 2005). This technique has been applied successfully to large samples of various spectral types including DA stars from the ESO SN Ia Progenitor Survey (Koester et al. 2009), from the Villanova Catalog of Spectroscopically Identified White Dwarfs (Gianninas et al. 2011), and in particular from the Sloan Digital Sky Survey (SDSS; Kepler et al. 2007; Tremblay et al. 2011). The same spectroscopic technique has also been used for DB stars (Kepler et al. 2007; Voss et al. 2007; Bergeron et al. 2011). Similarly, optical and infrared photometry can be combined and compared with synthetic photometry to measure effective temperatures, as well as stellar radii when trigonometric parallaxes are available. This photometric technique, first applied to large photometric data sets by Bergeron et al. (1997, 2001), is particularly useful to study cool white dwarfs that lack the presence of strong absorption lines required by the spectroscopic method. Particularly interesting in this context is the large set of optical ugriz photometry available for white dwarfs in the SDSS, combined with independent $JHK$ photometry (see, e.g., Kilic et al. 2010; Gianninas et al. 2015). The photometric approach, however, is more sensitive to issues related to the calibration of the synthetic photometry (Holberg & Bergeron 2006), unlike the spectroscopic approach.

Several independent model atmosphere grids have been widely used for the analysis of white dwarf stars (e.g., Bergeron et al. 1992; Vennes 1992; Koester et al. 2001), and the results obtained from these models are reassuringly comparable (see Figure 9 of Liebert et al. 2005). Despite this agreement between models, significant improvements on the theoretical front are still being achieved. For instance, new calculations for the Stark broadening of hydrogen lines that include nonideal effects directly inside the line profile calculations have recently become available (Tremblay & Bergeron 2009). These models yield systematically higher $T_{\text{eff}}$ (up to 1000 K) and $\log g$ (up to 0.1 dex) values, and a mean mass for DA stars shifted by +0.034 $M_\odot$. Similarly, Kowalski & Saumon (2006) have successfully modeled the opacity from the red wing of Ly$\alpha$, an important absorption process that affects the flux in the ultraviolet region of the energy distribution of cool, hydrogen-atmosphere white dwarfs. More
importantly perhaps, Tremblay et al. (2013b, see also Tremblay et al. 2011, 2013a) have produced realistic three–dimensional (3D) hydrodynamical model atmospheres of hydrogen-rich white dwarfs and successfully showed that the so-called high-\( \log g \) problem—the apparent increase of spectroscopic \( \log g \) values below \( T_{\text{eff}} \sim 13,000 \text{K} \) (see Tremblay et al. 2010 and references therein)—was related to the limitations of the mixing-length theory used to describe the convective energy transport in previous model atmosphere calculations.

With the availability of large data sets and improved model atmospheres, the statistical properties of white dwarf stars can now be studied in greater detail, including the luminosity function, space density, mass distribution, age distribution, and space kinematics. This can be achieved not only for the local population of white dwarfs, but also for various components of the Galaxy, including open and globular clusters (see, e.g., Tremblay et al. 2012; Woodley et al. 2012). Since white dwarfs represent the endpoint of over 97% of the stars in the Galaxy, they are a powerful tool to study the overall evolutionary history of the Galaxy. However, the determinations of these global properties are always confronted with the problem of defining statistically complete samples, minimally affected by selection biases. For instance, ultraviolet color excess surveys such as the Palomar–Green (PG) survey (Green et al. 1986) or the Kiso Schmidt (KUV) ultraviolet excess survey (Kondo et al. 1984) are restricted to the detection of blue and thus hot white dwarfs. Consequently, the luminosity functions derived from these surveys (Liebert et al. 2005; Limoges et al. 2010; Bergeron et al. 2011) do not sample the faint end of the distribution where the majority of white dwarf stars are located. Even the luminosity function determined by Harris et al. (2006) using the magnitude-limited SDSS sample, which covers the entire range of bolometric magnitudes \( (7 \lesssim M_{\text{bol}} \lesssim 16) \), includes several corrections for completeness and contamination to counterbalance important selection effects, and these corrections critically determine the faint end of the luminosity function. It is however possible, as shown by Kilic et al. (2006), to refine the selection criteria by combining the SDSS photometry and astrometry with the USNO-B plate astrometry to build a reduced proper motion diagram, which helps to identify cool white dwarf candidates in the SDSS imaging area and thus recover the faint end of the luminosity function. White dwarfs identified in proper motion surveys are indeed much better suited to identify cool white dwarfs at the faint end of the luminosity function. For many years, one of the most commonly used observational luminosity functions had been that published by Liebert et al. (1988), and revised by Leggett et al. (1998), based on the Luyten Half-Second Catalog (Luyten 1979), but the major drawback is that the sample contains only 43 spectroscopically confirmed white dwarfs.

Other types of statistical biases occur in determining the distribution of mass as a function of effective temperature \( (M \text{ versus } T_{\text{eff}}) \), or the cumulative mass distribution \( (N \text{ versus } M) \). For instance, color excess surveys (PG, KUV, and even SDSS) are also magnitude-limited, and as such the samples drawn from these surveys suffer from a bias in mass where low-mass white dwarfs with their large radii and high luminosities are over represented, while high-mass white dwarfs are undersampled (see, e.g., Section 3.2 of Liebert et al. 2005). Another important issue is that until recently spectroscopic masses at low effective temperatures could not be trusted due to the high-\( \log g \) problem discussed above. Thus, most analyses restricted their determination of the mass distribution of DA stars to temperatures higher than 13,000 K. Alternatively, Giammichele et al. (2012) applied an empirical correction to the \( \log g \) distribution, based on the DA white dwarfs from the Data Release 4 of the SDSS analyzed by Tremblay et al. (2011). More recently, Tremblay et al. (2013b) produced a more accurate set of \( T_{\text{eff}} \) and \( \log g \) corrections to be applied to spectroscopic determinations, based on a comparison of detailed 3D hydrodynamical simulations with one–dimensional (1D) model atmospheres calculated within the mixing length theory. Another problem arises at low effective temperatures when spectroscopic lines can no longer be used efficiently. This occurs below \( T_{\text{eff}} \sim 13,000 \) and \( \sim 6500 \text{K} \) for helium- and hydrogen-atmosphere white dwarfs, respectively, i.e., near the peak of the luminosity function, in which cases one must rely on the photometric technique to measure the atmospheric parameters. With the photometric technique, unfortunately, stellar radii or masses can only be determined for white dwarfs with trigonometric parallax measurements, which are only available for 200 stars or so. This situation will of course change dramatically when the Gaia mission is completed.

Also of interest is the study of the spectral evolution, which describes the various physical mechanisms (gravitational settling, convective mixing, convective dredge-up from the core, accretion from the interstellar medium or circumstellar material, radiative acceleration, stellar winds, etc.) that affect the surface composition of white dwarfs as they evolve along the cooling sequence. Of particular interest is the spectral evolution of white dwarfs at low \( T_{\text{eff}} \) where convective mixing of a thin superficial hydrogen convective layer with the deeper helium convection zone is believed to occur (see Tremblay & Bergeron 2008 and references therein). Bergeron et al. (1997, 2001) also suggested the presence of a non-DA gap (or deficiency) between \( T_{\text{eff}} \sim 5000 \) and \( 6000 \text{K} \) where most stars appear to have hydrogen-rich compositions, while helium-atmosphere white dwarfs exist above and below this temperature range. On the other hand, Kowalski & Saumon (2006, see also Giammichele et al. 2012) suggested that most if not all cool DC stars probably have hydrogen-rich atmospheres, based on a re-analysis of the Bergeron et al. (1997, 2001) photometry with their improved atmospheric models, which include the previously missing red wing opacity from Ly\( \alpha \). Unfortunately, the white dwarf samples analyzed by Bergeron et al. (1997, 2001) are not complete in any statistical sense. For instance, Kilic et al. (2010) analyzed 126 cool white dwarfs identified in the SDSS and uncovered several helium-atmosphere white dwarfs in the \( T_{\text{eff}} \) range of the gap. To complicate matters, Chen & Hansen (2011, 2012) showed that the evolution of cool white dwarfs cannot be interpreted monotonically as a function of \( T_{\text{eff}} \), and that upon mixing the \( T_{\text{eff}} \) of a white dwarf can actually increase. Hence our understanding of the spectral evolution of cool white dwarfs is at best sketchy, a situation that can only be improved by studying better-defined, large, statistically complete samples.

The best way around the completeness problems discussed above is the use of a volume-limited sample. Efforts to identify white dwarfs in the immediate solar neighborhood, within 20 or 25 pc of the Sun, have been summarized in Limoges et al. (2013, hereafter Paper I). Giammichele et al. (2012) performed a detailed photometric and/or spectroscopic analysis of every white dwarf suspected to lie within 20 pc of the Sun. Although Holberg et al. (2008) and Giammichele et al. (2012) have
established the completeness of the 20 pc sample at 80% and 90%, respectively, one is confronted with small number statistics since this sample contains only 130 objects or so. Hence some results reported by Giannichele et al. may not be statistically significant. For example, while the luminosity function shown in their Figure 22 agrees well with previous investigations at low temperatures and luminosities, space densities in the brighter luminosity bins (above $T_{\text{eff}} \approx 12,000$ K) are larger by a factor of $\sim$2. As mentioned by the authors, one likely explanation for this apparent overdensity is the small number of white dwarfs in the brightest luminosity bins, which contain only a few objects ($\sim$2–8). The only way out of this situation is to significantly increase the volume sampled by these surveys. For instance, Holberg et al. (2011) are working on defining the sample of white dwarfs to 25 pc of the Sun, nearly doubling the number of objects analyzed by Giannichele et al. (2012).

It is with this idea in mind that we embarked on a large effort (see Paper I) to increase the census of white dwarfs to the larger distance range of 40 pc from the Sun (corresponding to a volume 8 times that of the 20 pc sample). Given the space density of $4.39 \times 10^{-3}$ pc$^{-3}$ derived by Giannichele et al. (2012), the expected number of white dwarfs within 40 pc is $\sim$1200, or $\sim$600 if we restrict our search to the northern hemisphere, a sample size that would markedly improve the statistical significance of previous analyses. The SUPERBLINK survey is an all-sky search for high proper motion stars ($\mu > 40$ mas yr$^{-1}$) based on a re-analysis of the Digitized Sky Surveys, with its 20–45 years baseline (Lépine & Shara 2005; Lépine & Gaia 2011). The SUPERBLINK catalog is at least 95% complete for the entire northern sky down to $V = 19.0$, with a very low rate of spurious detection. As discussed in Paper I, the SUPERBLINK catalog should contain all white dwarfs down to the luminosity function turnover (which occurs at $L/L_\odot \approx 10^{-3}$) to a distance of 56.7 pc from the Sun. Our method for selecting white dwarf candidates, described in detail in Paper I, is based on reduced proper motion diagrams of the 1.6 million stars in SUPERBLINK with $\delta > 0$, combined with distances estimated from theoretical color–magnitude relations. A list of 1341 candidates with photometric distance estimates of $D < 40$ pc, to within the uncertainties, was established for follow-up spectroscopic observations, excluding the objects with an already known spectral type. We successfully confirmed 193 new white dwarfs, among which 93 had spectroscopic distances placing them within 40 pc. Only DA stars with strong enough Balmer lines were analyzed in Paper I, using the spectroscopic method described above.

The specific goal of this work is to obtain a complete sample of white dwarfs within 40 pc of the Sun in the northern hemisphere. We report in this paper the outcome of our survey, and present a detailed photometric and spectroscopic model atmosphere analysis of all the new white dwarfs that were identified. We also provide a comprehensive analysis of the mass distribution and the chemical distribution of white dwarf stars in this volume-limited sample. In particular, since only about a third of the white dwarfs in our sample have trigonometric parallax measurements available, we develop a robust method to derive distances from spectroscopic and photometric data alone.

We first present in Section 2 an update of our census of white dwarfs within 40 pc of the Sun, which includes a summary of our earlier work as well as a detailed description of the follow-up spectroscopic observations of our list of white dwarf candidates. We then perform in Section 3 a detailed photometric and spectroscopic analysis of all objects in our sample with state-of-the-art model atmospheres, where we also include all known white dwarfs in the SUPERBLINK catalog and from the literature, suspected to belong to the 40 pc sample. The resulting distance estimates are then used to build a complete sample of white dwarfs within 40 pc of the Sun, which we analyze in further detail in Section 4. In particular, we discuss several physical properties of this sample, including its completeness, kinematics, mass distribution, spectral evolution, and luminosity function. We then offer some concluding remarks in Section 5.

2. UPDATE ON OUR CENSUS OF WHITE DWARFS WITHIN 40 pc OF THE SUN

2.1. Selection of the Candidates Based on Reduced Proper Motion Diagrams

Our method for selecting white dwarf candidates from the SUPERBLINK catalog using reduced proper motion diagrams is discussed at length in Paper I. We briefly summarize here, for completeness, the various steps involved.

The white dwarf candidates are identified from the SUPERBLINK catalog of stars with proper motions $\mu > 40$ mas yr$^{-1}$ (Lépine et al. 2002; Lépine & Shara 2005; Lépine & Gaia 2011). Our selection method takes advantage of the coordinates and proper motions provided by SUPERBLINK for 1,567,461 stars in the northern hemisphere ($\delta > 0$). White dwarf candidates are selected on the basis of their particular location at the bottom left of reduced proper motion diagrams. Since the construction of such diagrams requires, in addition to proper motion measurements, a set of photometric color indices for each star, we cross-correlate SUPERBLINK with other catalogs to obtain photometric data covering a large portion of the electromagnetic spectrum, and in some cases, we also obtain improved coordinates and proper motion measurements. Our version of SUPERBLINK used in Paper I includes—in the northern hemisphere only—1,472,666 counterparts in the 2MASS Point Source Catalog (Skrutskie et al. 2006), 345,958 in the SDSS (Adelman-McCarthy et al. 2008), 118,475 in the Hipparcos and Tycho-2 catalogs (Høg et al. 2000), 1,567,461 in the USNO-B1.0 database (Monet et al. 2003), and 143,096 in the sixth data release of the GALEX database (Gil de Paz et al. 2009). Each object in SUPERBLINK with $\delta > 0$ is then placed in all corresponding ($H_m$, color-index) diagrams, depending on the available photometry, where $H_m$ represents the reduced proper motion defined as $H_m = m + 5 \log_{10} \mu + 5$, $m$ is the apparent magnitude in some bandpass, and $\mu$ is the proper motion measured in arcseconds per year. More specifically, we rely on $(H_g, g - z)$ based on uvgriz photometry, $(H_v, V - J)$ based on UV GALEX photometry, $(H_v, V - J)$ based on 2MASS $JHK_s$ photometry, and $(H_v, V - I_S)$ based on USNO-B1 photographic magnitudes. We also restrict our search to stars with $V < 19$, since SUPERBLINK has an estimated false detection level of less than 1% down to $V = 19$, but the false detection rate increases significantly for fainter sources.

The limit that defines the white dwarf region in each diagram is determined from the location of SUPERBLINK objects with known white dwarf counterparts in the 2008 May electronic version of the Catalog of Spectroscopically
Identified White Dwarfs\textsuperscript{5} (McCook & Sion 1999, hereafter WD Catalog). To be selected as a white dwarf candidate, a SUPERBLINK object must be identified in the expected white dwarf region of the diagram with the most accurate photometry. The highest priority is thus given to the reduced proper motion diagram based on SDSS magnitudes. If $ugriz$ photometry is not available, the second priority is given to UV GALEX photometry, the third priority to 2MASS $JHK_s$ photometry, and if no other photometric system is available, we use USNO-B1 photographic magnitudes. Finally, a criterion in $V - J$ is applied to the stars identified in $(H_V, V - J)$ diagrams to exclude bright, red, main sequence (MS) contaminants.

Since we want to restrain our survey to a distance less than $D = 40$ pc from the Sun, and in the absence of trigonometric parallax measurements for most white dwarf candidates in our sample, we must rely on photometric distances estimated from the distance modulus, $m - M = 5 \log D - 5$, where the absolute magnitude $M$ of each object is determined from theoretical color–magnitude relations combined with a measured color index in some specified photometric system. These theoretical relations at constant mass values (see Figures 5–8 of Paper I) are based on synthetic photometry from white dwarf model atmospheres, following the procedure described in Holberg & Bergeron (2006). Hence, absolute magnitudes for each white dwarf candidate are determined from color–magnitude relations in $(M_g, g - z)$, $(M_V, NUV - V)$, $(M_V, V - J)$ or $(M_V, V - I_s)$, for a $0.6 M_\odot$ hydrogen-atmosphere sequence, and for a helium-atmosphere sequence at the same mass in order to evaluate the distance uncertainty resulting from the unknown atmospheric composition of our candidates. A comparison of these photometric distances with those obtained from parallax measurements shows a $\sigma$ dispersion of 8.5 pc (see Figure 9 of Paper I), and we thus adopt in our survey a conservative buffer of 15 pc to include all white dwarfs that could potentially lie within 40 pc of the Sun, that is with $D_{\text{phot}} < 55$ pc.

The method described above led to the identification of 193 new spectroscopically identified white dwarfs in Paper I. However, even though 14594+3618 (we omit here and below the letters “PM I” from the designation) was identified as a white dwarf in Paper I, a new spectrum at a significantly improved S/N shows that the star is an MS F star, hence reducing the total of new white dwarfs identified to 192. We also established that our survey is efficient at identifying nearby white dwarfs distributed uniformly across the northern sky, and estimated the ratio of new to known white dwarfs to be around 77% within 40 pc. More importantly, our survey has identified a large amount of cool white dwarfs that could possibly refine the determination of the faint end of the luminosity function. We describe in the next section the update of our spectroscopic survey.

2.2. Spectroscopic Follow-up of White Dwarf Candidates within 40 pc of the Sun

In Paper I, we compiled a list of 1341 white dwarf candidates within 40 pc of the Sun—but likely extending to 55 pc given the uncertainties—and reported spectroscopic observations for 422 objects from this target list, including 192 new white dwarf identifications. We also reported that our selection criteria recovered 499 known nearby white dwarfs from the literature (see Figure 11 of Paper I). However, a thorough search indicated that while several of these objects have a WD spectral classification in Simbad, they have never been confirmed spectroscopically (and indeed, some of these turned out not to be white dwarfs after all). We also improved the cross-correlation of objects in our target list with known white dwarfs from the literature, and discovered several improper matches. Hence the number of previously known, actual white dwarfs identified from our selection criteria is 416. Finally, we have recently determined that our criterion based on $V - J$ color used to exclude bright, red, MS contaminants (see above) had not in fact been applied to our list of white dwarf candidates. Taking all these changes into account, our list of white dwarf candidates now numbers 1180 objects.

The spectroscopic observing log of our earlier survey is presented in Table 2 of Paper I. Since then, additional optical spectra have been obtained with the Steward Observatory 2.3 m telescope and the NOAO Mayall 4 and 2.1 m telescopes during 7 different observing campaigns between 2011 January and 2013 October. A few of the brightest candidates were also observed in spectroscopy with the 1.6 m Mont-Mégantic Observatory, while $\sim$60 hr with the Gemini North and South 8 m telescopes were used to observe our faintest candidates ($V \approx 17–18$). The adopted configurations allow a spectral coverage of $\lambda \sim 3200–5300$ Å and $\sim 3800–6700$ Å, at an intermediate resolution of $\sim 6$ Å FWHM. Spectra were first obtained at low S/N ($S/N \sim 25$), which is sufficient to identify MS objects, but also represents the lower limit required to obtain reliable model fits to the spectral lines. However, some stars were reobserved at higher S/N and resolution, whenever required. Table 1 summarizes our spectroscopic observation campaigns carried out since Paper I, along with their instrumental setups.

We have now secured spectra for 588 objects from our list of 1180 candidates, thus adding 163 spectra to the list of 422 objects reported in Paper I. The content of our complete spectroscopic data set, described in the next subsection, includes 325 new white dwarf identifications (192 reported in Paper I), and 263 spectra from contaminants, mainly MS stars and quasars. We note that 3 of the newly identified white dwarfs are included in the SDSS Data Release 7 but were not classified as such; we rely on the corresponding SDSS spectra for these stars.

The current state of our survey is summarized in Figure 1 (upper panel), which plots the estimated absolute visual magnitudes (from the calculated $V$ magnitudes and photometric distances—see Paper I) as a function of the photometric distance for the 325 new white dwarfs (filled symbols) and the 416 previously known white dwarfs (open symbols). We note that the subset of new white dwarfs is dominated by objects fainter than $V = 16$, and that most of them are found at photometric distances larger than 20 pc. The 592 white dwarf candidates on our list still without spectroscopic confirmation are displayed separately in the lower panel of Figure 1; objects selected on the basis of the less reliable USNO photographic magnitudes (crosses) are considered second priority targets because of their higher probability of being main-sequence contaminants. If we exclude these second priority targets, we are left with $\sim 330$ first-priority candidates for the spectroscopic follow-up survey. However, only 4 candidates with $D < 30$ pc and $V < 18$ remain to be observed, and every candidate with a high probability of being a white dwarf with an estimated distance less than 20 pc has been observed.

\textsuperscript{5} http://www.astronomy.villanova.edu/WDCatalog/index.html
Table 1
Spectroscopic Observing Runs

| Date   | Telescope          | Spectrograph | Grating (l/mm⁻¹) | Blaze (Å) | Coverage (Å) | Slit (°) |
|--------|--------------------|--------------|------------------|----------|--------------|----------|
| 2011 Jan | NOAO 2.1 m         | Goldcam      | 500              | 5500     | 3800-6700    | 2        |
| 2011 Mar | NOAO Mayall 4 m    | RC           | 316              | 5500     | 3900-6700    | 2        |
| 2011 Apr | Steward Observatory Bok 2.3 m | B&C       | 600              | 3568     | 3800-5600    | 4.5      |
| 2011 Apr | NOAO 2.1 m         | Goldcam      | 500              | 5500     | 3800-6700    | 2        |
| 2012 Sep | NOAO Mayall 4 m    | RC           | 316              | 5500     | 3900-6700    | 2        |
| 2011 B   | Gemini North       | GMOS-N       | 600              | 4610     | 3800-6700    | 1        |
| 2011 B   | Gemini South       | GMOS-S       | 600              | 4610     | 3800-6700    | 1        |
| 2012 B   | Gemini North       | GMOS-N       | 600              | 4610     | 3800-6700    | 1        |
| 2013 Jan | Observatoire du Mont-Mélangic 1.6 m | B&C       | 600              | 4000     | 3800-6700    | 4.3      |
| 2013 Jun | Steward Observatory Bok 2.3 m | B&C       | 600              | 3568     | 3800-5600    | 4.5      |
| 2013 Oct | Steward Observatory Bok 2.3 m | B&C       | 600              | 3568     | 3800-5600    | 4.5      |

Figure 1. Absolute visual magnitude as a function of photometric distance for spectroscopically confirmed white dwarfs (top) and our remaining candidates (bottom). In the upper panel, the filled circles represent the 325 new white dwarfs identified in our survey, while the open circles correspond to the 416 white dwarfs already known in the literature. Dashed lines in the Figure are lines of constant apparent V magnitudes. The 592 remaining white dwarf candidates in our survey, still awaiting spectroscopic confirmation, are shown in the lower panel. Lower-priority candidates (those identified on the basis of USNO photographic magnitudes and those with V > 18) are shown with cross symbols.

2.3. Spectroscopic Content of our Updated Survey

Our spectroscopic follow-up observations from 2011 January to 2013 October (Table 1) have led to the identification of the 133 new white dwarfs listed in Tables 2 and 3 (including the 3 SDSS white dwarfs discussed above). Table 2 provides astrometric data as well as NLTT and SDSS designations, when available, while Table 3 lists the available photometry and adopted spectral types for the same objects. Since Paper I, the SUPERBLINK catalog has been updated with optical magnitudes from the 7th Data Release of the SDSS catalog, and ultraviolet magnitudes from the DR4-5 data release of GALEX. In particular, the number of stars with GALEX counterparts has increased to 258,076 objects, while the number of stars with SDSS counterparts now reaches 740,826. This improved photometry is essential for the analysis of the energy distribution of the SUPERBLINK white dwarfs, as well as for the estimation of their distances. For this reason, we also include in Table 3 revised photometry for the 192 new white dwarfs identified in Paper I. In summary, the new white dwarfs reported in this paper comprise 96 DA (including 1 DAZ, 3 DA +dM, and 5 magnetics), 3 DB, 24 DC, 3 DQ, and 7 DZ (including 1 DZA) stars.

Our new DA spectra are displayed in Figures 2 and 3; only Hα is displayed in Figure 3 since the bluer portion of the spectrum is either featureless or too noisy to be of any use in the coolest DA stars. We also show at the bottom of the last panels of Figures 2, 3 new spectra of stars already presented in Table 4 of Paper I, that are double degenerate binary candidates and are further analyzed below. Note that 05431+3637 is actually a DAZ star. Two of the DA stars discovered in our survey—06018+2751 (GD 258) and 18435+2740 (GD 381)—were flagged as WD candidates in Giclas et al. (1980), but to our knowledge these had not been spectroscopically confirmed, suggesting that many of the Giclas objects may still be white dwarfs awaiting spectroscopic confirmation. The magnetic DA white dwarfs, or magnetic candidates, in our updated sample are displayed in Figure 4. The bottom five objects are new identifications, with the Zeeman triplets clearly visible despite their low S/Ns. The top object, 04523+2519, was initially flagged as non-magnetic in Paper I, but the flat bottom line cores observed in our spectroscopic fit (see Figure 17 of Paper I) led us to reobserve this star at Hα, where the weak Zeeman splitting is now just barely detected, making us believe this star is magnetic as well. Finally, our survey also led to the discovery of 3 new DA + M dwarf binary systems, shown separately in Figure 5.

Our subsample of new DZ (DZA), DB (DBA), and DQ stars is displayed in Figure 6. The first object in the figure, 00050+4003, is the star GD 1, another WD candidate listed in Giclas et al. (1980). Also shown are 5 DZ stars already identified in Paper I but for which new optical spectra in the blue have been secured: 01216+3440, 03196+3630, 16477+2636, 21420+2252, and 23003+2204. Indeed, the observational setup used with the 2.1 and 4 m NOAO telescopes does not allow simultaneous coverage of wavelengths shorter than 3900 Å and of Hα in the red. In order to better constrain the metal abundances in these objects, additional spectra covering the blue portion of the spectral energy distribution were thus obtained with the Steward Observatory 2.3 m Bok telescope. The 3 new DB white dwarfs displayed in Figure 6 also include 02236+4816, also known as...
GD 27, another WD candidate from Giclas et al. (1980) that was also lacking spectroscopic confirmation to this date. Finally, our 3 DQ spectra, some of which are easily recognizable from their strong C₂ Swan bands, are shown in the bottom right section of Figure 6; 16142+1729 is actually one of those peculiar DQ stars with shifted C₂ Swan bands referred to as DQpec white dwarfs, a phenomenon explained by Kowalski (2010) as a result of pressure shifts of the carbon bands that occur in very cool, helium-dominated atmospheres. 05449+2602 has a DC spectral type in the WD Catalog (WD 0541+260) but this spectral classification was erroneously taken from Table 2 of Limoges et al. (2010), where it was confused by McCook & Sion with 00056+4825. 01327+6635 is actually one of those peculiar DQ stars, it was classified as a DQ? star in Table 3, although it could also be magnetic.

Finally, our featureless DC spectra are displayed in Figure 7 in order of R.A. All spectra cover the λ ~ 3900–6700 Å range, except for 05462+1115 for which only the blue part of the spectrum (λ < 5200 Å) is available, and we notice a few cases where the blue portion of the spectrum is particularly noisy, preventing us from detecting the possible presence of calcium lines. These noisier spectra actually come from Gemini North and South, where the integration times were calculated for the central wavelengths near 5000 Å, but the gratings used with the GMOS-N and -S instruments (B600 G5307), chosen for their spectral coverage, have a quantum efficiency that falls below 43% blueward of 3937 Å, compared with 83% at 4983 Å.

The progress of our spectroscopic survey can also be summarized in the color–color diagram shown in Figure 8, where we display the subset of 151 spectroscopically confirmed white dwarfs in our sample that also have available ugriz photometry from SDSS. White dwarf candidates without spectroscopic confirmation are shown in red, and most of these have estimated distances larger than 30 pc, as can be seen from Figure 1. This figure reveals that our sample of new white dwarfs is composed mainly of DA stars, but also contains a significant number of cool (Teff < 5000 K) white dwarfs, with objects as cool as 4000 K.

Finally, the entire white dwarf population detected in SUPERBLINK is presented in Figure 9, where we display its distribution on the sky. In the upper panel, the 325 new identifications are shown with solid dots, while the white dwarfs from the literature are represented with open circles. In the bottom panel, we plot the sky density as a function of R.A. and declination and compare it to that of the 325 new identifications (dashed line) and to the sum of the old and new white dwarfs (solid line). In Paper I, Figure 11 showed that the white dwarf candidates in our survey had the potential to fill the void left in the galactic plane by earlier surveys. Here we note that the density of new identifications, especially near R.A. = 100, suggests we are on our way to identifying the missing white dwarfs in this particular region of the sky.

| PM I    | NLTT | SDSS | R.A. (J2000) | Decl. (J2000) | µ RA  | µ RA  | µ DE  |
|---------|------|------|--------------|--------------|-------|-------|-------|
| 00050+4003 | 133  | ...  | ...          | +00:05:01.08 | +40:03:34.6 | 0.229 | 0.206 | 0.101 |
| 00056+4825 | ...  | ...  | +00:05:40.41 | +48:25:05.9  | 0.153 | 0.152 | -0.013 |
| 00074+3403 | 301  | ...  | +00:07:28.87 | +34:03:39.9  | 0.199 | 0.201 | 0.197 |
| 01088+7600 | ...  | ...  | +01:08:49.61 | +76:00:18.4  | 0.242 | 0.237 | 0.050 |
| 01278+7328 | 4799 | ...  | +01:27:49.09 | +73:28:47.7  | 0.177 | -0.160 | 0.076 |
| 01327+4600 | 5100 | ...  | +01:32:46.67 | +46:04:58.8  | 0.211 | -0.211 | -0.002 |
| 01327+6635 | ...  | ...  | +01:32:42.90 | +66:35:46.0  | 0.051 | 0.039 | -0.033 |
| 01390+2402 | ...  | ...  | +01:39:00.18 | +24:02:58.8  | 0.096 | 0.094 | -0.021 |
| 01534+3557 | ...  | ...  | +01:53:28.98 | +35:57:29.2  | 0.175 | 0.174 | -0.020 |

This table is available in its entirety in machine-readable form.

| PM I    | FUV | NUV | B_F | R_F | I_N | J   | H   | K_S | a   | g   | r   | i   | z   | ST | Notes |
|---------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|------|
| 00023+6357 | ...  | ...  | 17.8 | 16.2 | 17.3 | 15.80 | 15.57 | 15.51 | ... | ... | ... | ... | ... | DC  | ...  |
| 00050+4003 | 18.14 | 16.3 | 16.2 | 16.5 | ... | ... | ... | ... | ... | ... | ... | ... | ... | DZA | ...  |
| 00056+4825 | 19.38 | 17.1 | 16.9 | 16.5 | 16.25 | 15.60 | 15.89 | ... | ... | ... | ... | ... | ... | DA  | ...  |
| 00074+3403 | 21.07 | 17.7 | 17.3 | 16.8 | 16.39 | 16.25 | 15.83 | ... | ... | ... | ... | ... | ... | DC  | ...  |
| 00079+3947 | ... | 17.4 | 16.2 | 15.8 | 15.18 | 14.85 | 14.65 | ... | ... | ... | ... | ... | ... | DC  | ...  |
| 00217+2640 | ... | 17.9 | 17.2 | 16.9 | 16.18 | 15.91 | 15.81 | ... | ... | ... | ... | ... | ... | DC  | ...  |
| 00276+0542 | ... | 17.2 | 15.6 | 15.4 | 14.97 | 14.67 | 14.57 | ... | ... | ... | ... | ... | ... | DA  | ...  |
| 00331+4728 | 14.55 | 14.63 | 14.9 | 14.9 | 15.16 | 15.02 | 15.14 | ... | ... | ... | ... | ... | ... | DA  | ...  |
| 00334+2506 | ... | 20.36 | 16.6 | 16.6 | 16.1 | 15.96 | 15.70 | 15.45 | 17.88 | 17.12 | 16.79 | 16.69 | 16.68 | DA | ... |

Notes. (1) WD in McCook and Sion (2012). (2) Also in Schilbach and Röser (2012). (3) Also in Vennes et al. (2011). (4) SDSS spectrum. (5) Also in Sayres et al. (2012). (6) Also in Kilic et al. (2010). (7) DA+dM in Rebassa-Mansergas et al. (2010). (8) Also in Touty et al. (2012). (9) LSPM J1227+3150 wrongly identified as PM 11227+3150 in Limoges et al. (2013). This table is available in its entirety in machine-readable form.
3. ATMOSPHERIC PARAMETER DETERMINATION

3.1. Theoretical Framework

Our model atmospheres and synthetic spectra for hydrogen-atmosphere white dwarfs are built from the model atmosphere code originally described in Bergeron et al. (1995) and references therein, with recent improvements discussed in Tremblay & Bergeron (2009). These are pure hydrogen, plane-parallel model atmospheres, with non-local thermodynamic equilibrium effects explicitly taken into account above $T_{\text{eff}} = 30,000\, \text{K}$, and energy transport by convection included in cooler models following the ML2/$\alpha = 0.7$ prescription of the mixing-length theory. The theoretical spectra are calculated within the occupation probability formalism of Hummer & Mihalas (1988), which provides a detailed treatment of the level populations as well as a consistent description of bound–bound and bound–free opacities. We also include the improved calculations for the Stark broadening of hydrogen lines from

Figure 2. Optical spectra for our new, spectroscopically confirmed DA white dwarfs, displayed in order of decreasing effective temperature (upper left to bottom right) and shifted vertically for clarity; 05431+3637 is a DAZ star. The H$\alpha$ line is also shown when available, and normalized to a continuum set to unity. The last three spectra at the bottom of the right panel are new observations of stars already presented in Paper I that are double degenerate binary candidates.
Tremblay & Bergeron (2009), which take into account nonideal perturbations from protons and electrons directly inside the line profile calculations, as well as the opacity from the red wing of Ly\(\alpha\) calculated by Kowalski & Saumon (2006), which is known to affect the flux in the ultraviolet region of the energy distribution, and in particular the far-ultraviolet (FUV), NUV, and \(u\) magnitudes used in our analysis. Our model grid covers a range of effective temperatures between \(T_{\text{eff}} = 1500\) and 120,000 K in steps of 250 K for \(T_{\text{eff}} < 5500\), 500 K up to \(T_{\text{eff}} = 17,000\), and 5000 K above. The log \(g\) ranges from 6.0 to 9.5 by steps of 0.25 dex. We also calculated cooler models with mixed hydrogen and helium compositions (see Gianninas et al. 2015) for the analysis of white dwarfs in our sample that show evidence for collision-induced absorptions by molecular hydrogen due to collisions with helium.

Our model atmospheres and synthetic spectra for helium-atmosphere stars are described at length in Bergeron et al. (2011). These include the Stark profiles of neutral helium from Beauchamp et al. (1997) as well as van der Waals broadening.
The synthetic spectra are calculated using the occupation probability formalism of Hummer & Mihalas (1988) for helium populations and corresponding bound–bound, bound–free, and pseudo-continuum opacities. Our model grid covers a range of effective temperatures between $T_{\text{eff}} = 3000$ and 40,000 K in steps of 1000 K, while the log $g$ ranges from 7.0 to 9.0 in steps of 0.5 dex. In addition to pure helium models, we also calculated models above 11,000 K with log H/He = −6.5 to −2.0 by steps of 0.5 dex.

The photometric analyses of DQ and DZ white dwarfs rely on the LTE model atmosphere calculations developed by Dufour et al. (2005, 2007) for the study of DQ and DZ stars, respectively. Both are based on a modified version of the code described in Bergeron et al. (1995). The main addition to the models is the inclusion of metals and molecules in the equation of state and opacity calculations. These heavier elements provide enough free electrons to affect the atmospheric structures and predicted energy distributions of cool, helium-rich white dwarfs.

### 3.2. Photometric Analysis

#### 3.2.1. General Procedure

The photometric technique developed by Bergeron et al. (1997) makes use of the apparent magnitudes in any photometric system in order to measure the atmospheric parameters ($T_{\text{eff}}$ and log $g$) and the chemical composition. This method is particularly useful for the analysis of cool white dwarfs when spectral features are either too weak or completely absent. The magnitudes in each bandpass are first converted into a set of average fluxes $f_{\lambda}^m$ following the procedure described in Holberg & Bergeron (2006), which is mainly based on the Vega fluxes from Bohlin & Gilliland (2004), but also includes $ugriz$ photometry in the AB magnitude system. In particular, here we make use of the transmission functions described in Morrissey & GALEX Science Team (2004) and available from the GALEX Web site for the FUV and NUV filters, while the bandpasses for the $ugriz$ system (Fukugita et al. 1996) are taken from the SDSS Web site. Similarly, for the 2MASS filters described in Cohen et al. (2003), we use the transmission functions from the 2MASS survey Web site. Finally, the USNO-B1.0 $B_\pi$, $R_\pi$, and $I_N$ magnitudes are described in Monet et al. (2003), and the transmission functions are taken from the Digitized Sky Survey website.

These observed average fluxes can be compared to the average model fluxes $H_{\lambda}^m$ by the relation

$$f_{\lambda}^m = 4\pi(R/D)^2 H_{\lambda}^m,$$

where $R/D$ defines the ratio of the radius of the star to its distance from Earth. The model fluxes $H_{\lambda}^m$—which depend on $T_{\text{eff}}$, log $g$, and chemical composition—are obtained from averages over the transmission function of the corresponding bandpass. We then minimize the $\chi^2$ value defined in terms of the difference between observed and model fluxes over all bandpasses, properly weighted by the photometric uncertainties. Our minimization procedure relies on the nonlinear least-squares method of Levenberg–Marquardt (Press et al. 1986), which is based on a steepest descent method. Only $T_{\text{eff}}$ and the solid angle $\pi(R/D)^2$ are considered free parameters (for an assumed chemical composition), while the error of both parameters is obtained directly from the covariance matrix of the fit. For stars with known trigonometric parallax measurements, we first assume a value of log $g = 8$ and determine $T_{\text{eff}}$ and the solid angle, which combined with the distance $D$ obtained from the trigonometric parallax measurement, yields directly the radius of the star $R$. The radius is then converted into mass using evolutionary models similar to those described in Fontaine et al. (2001) but with C/O cores, $q(\text{He}) \equiv \log M_{\text{He}}/M_\odot = 10^{-2}$ and $q(\text{H}) = 10^{-4}$, which are representative of hydrogen-atmosphere white dwarfs, and $q(\text{He}) = 10^{-2}$ and $q(\text{H}) = 10^{-10}$, which are representative of helium-atmosphere white dwarfs. In general, the log $g$ value obtained from the inferred mass and radius ($g = GM/R^2$) will be different from our initial assumption of log $g = 8$, and the fitting procedure is thus repeated until an internal consistency in log $g$ is reached. For white dwarfs with no parallax measurement, we simply assume a value of log $g = 8$ and an uncertainty of 0.25 dex, which corresponds approximately to a 2σ dispersion of the surface gravity distribution of hot DA stars (Gianninas et al. 2011).

---

6 http://GALEXgi.gsfc.nasa.gov/docs/GALEX/Documents/PostLaunchResponseCurveData.html
7 http://www.sdss.org/dr6/instruments/imager/#filters
8 http://www.ipac.caltech.edu/2mass/releases/allsky/doc/sec6_4a.html
9 http://www3.cadc-ccda.hia-iha.nrc-cnrc.gc.ca/dss/
10 This synthetic photometry is available at [http://www.astro.umontreal.ca/~bergeron/CoolingModels](http://www.astro.umontreal.ca/~bergeron/CoolingModels).
All others are new white dwarf discoveries.

Spectra of our newly identified DA white dwarfs, shifted vertically for clarity. 04523+2519 was classified as non-magnetic in Paper I. All others are new white dwarf discoveries.

3.2.2. Analysis with Hydrogen- and Helium-atmosphere Models

We first perform a photometric analysis of all featureless DC stars in our sample, and of all DA stars for which the Balmer lines are too weak to be analyzed with the spectroscopic method. Sample fits are shown in Figure 10 for a subsample of 5 newly identified white dwarfs. Average observed fluxes are represented by error bars in the left panels (with the photometric bandpasses used in the fitting procedure indicated at the top of each panel), while our best fits with pure hydrogen and pure helium models are shown as filled or open circles, respectively. The corresponding atmospheric parameters are given at the bottom of each panel. The USNO-B1.0 photographic magnitudes have an error of 0.5 mag, which explains the large error bars associated with their photometry. However, since the fit is weighted by the photometric uncertainty, these less accurate magnitudes will have little impact on the solution but they are still useful when no other photometric information is available. Also, some bandpasses had to be removed from the fitting procedure (shown in red in the left panels) either because they are obviously incorrect, or because they are contaminated by the presence of a red companion. In the right panels we compare the spectroscopic observations near Hα with the model predictions assuming the pure hydrogen solution; these only serve as an internal check of our photometric solutions and are not used in the fitting procedure. When Hα is observed spectroscopically, we adopt the pure hydrogen solution, as is the case for two objects in Figure 10, and even for magnetic DA stars (one shown in Figure 10). When Hα is predicted by the pure hydrogen solution but is not observed spectroscopically, we adopt the pure helium solution instead (see, e.g., second object from the top in Figure 10). In cases where the star is too cool to show Hα (T eff ≤ 5000 K), one has to rely on the predicted energy distributions to decide which atmospheric composition is best fit to the photometric data. However, according to Kowalski & Saumon (2006) based on their analysis of cool white dwarfs with models including the Lyα opacity, almost all cool DC stars appear to have hydrogen-rich atmospheres, a conclusion also reached by Giammichele et al. (2012, see their Figure 9 and their Section 4.2). We thus assume here the pure hydrogen solution for all cool DC stars in our sample (bottom object in Figure 10 for instance). Based on a close inspection of these photometric fits and predicted Hα features, we adopt the solution shown in red in the left panels.

The photometric fits for all 146 DC and cool DA stars in our sample are displayed in Figure 11. The particular case of the DZ star 12145+7822 will be discussed in Section 3.2.3. Also included here are the photometric fits to 3 DA + M dwarf systems (03031+2317, 04032+2520 E, and 08184+6606) hot enough to be analyzed with the spectroscopic method, but for which the optical spectra are so heavily contaminated by the presence of the companion that the spectroscopic technique cannot be used reliably. In those cases, we also had to omit from our photometric fits the Iα and JHKs magnitudes for 03031+2317, the Ri and JHKs for 04032+2520 E, and we kept only the Bi, Ri, and ugri magnitudes for 08184+6606. Figure 11 also includes the fits to 11 new magnetic white dwarfs identified in our survey. For these, the photometric technique is adopted since the presence of such small magnetic fields are not likely to affect the predicted energy distributions.

A closer inspection of all the photometric fits shown in Figure 11 reveals that most solutions for the DA stars predict an Hα feature that agrees remarkably well with observations (with the glaring exception of 04263+4820, 11337+6243, 11598+0007, and 14278+0532, discussed further in Section 3.4), giving us confidence in our photometric temperature scale, even for non-DA stars. Since we are often forced in our survey to rely on magnitudes with large uncertainties, we need to worry about the overall accuracy of the photometric method. But our results indicate that the lack of accurate photometric measurements for some objects is
compensated to some extent by the large number of data points, and also by the fact that the fit is weighted by the error on the photometry.

3.2.3. Photometric Analysis of DQ and DZ Stars

The photometric technique used to fit the energy distributions of DQ and DZ stars is similar to that described above for the cool DA and DC stars in our sample, with the exception that the abundance of heavy elements (carbon or metals) is determined from fits to the optical spectra (see also Giammichele et al. 2012). Briefly, the energy distribution is first fitted for an arbitrary abundance of heavy elements to obtain an initial estimate of the effective temperature (log g is assumed or constrained from trigonometric parallax measurements). The spectroscopic observations are then used to determine the carbon abundance in the case of DQ stars—fitting the C₂ Swan bands—or the metal abundances in the case of DZ stars—fitting the Ca II H & K doublet—at these initial values of Teff and log g. This improved determination of heavy element abundances is then used to obtain new estimates of the atmospheric parameters, and this procedure is repeated until a consistent photometric and spectroscopic solution is reached.

Results for the 5 new DQ stars in our sample (3 from Paper I and 2 from this work) are presented in Figure 12, where we display in the left panels the observed and model fluxes, as well as the adopted Teff, log g, and carbon abundance, and in the right panels, the observed and model spectra (for the DQ? star 05449+2602, we assumed a pure helium composition and our best fit is shown in Figure 11). The predicted energy distributions and spectra agree well for the two normal DQ stars shown at the top. The three other objects are DQpec white dwarfs, with characteristic pressure-shifted C₂ Swan bands (Kowalski 2010). Since these pressure shifts are not included in our models, the line strengths and shifts are not properly reproduced. For these DQpec stars, we simply fit/force the carbon abundance to reproduce the overall strength of the C₂ molecular bands, which is sufficient for our purposes. Note also that the effective temperature for 12476+0646 has been forced to Teff = 5000 K, which corresponds to the coolest temperature in our DQ model grid.

Figure 6. New spectra of DZ (DZA), DB (DBA), and DQ stars. Spectra for the DZ stars 01216+3440, 03196+3630, 16477+2636, 21420+2252, and 23003+2204 represent new higher S/N observations of stars reported in Paper I, used to better constrain the metal abundances.
The results for the 13 new DZ stars in our sample (6 from Paper I and 7 from this work) are presented in Figure 13, where the spectroscopic observations used to determine the calcium abundances in the fitting procedure are shown in the right panels. As mentioned above, the calcium abundances are determined from the strength of the Ca II H & K doublet (see also Dufour et al. 2007), while the abundance of other heavy elements, whether or not they are spectroscopically detected, are assumed to have solar ratios. Because hydrogen is often present in some of these DZ stars (DZA stars), we rely on model grids calculated with hydrogen abundances of $\log H/He = -3, -4,$ and $-5$. The insert in the right panels shows the Hα absorption line used to measure or constrain the hydrogen abundance in these stars. The Hα line is particularly strong in 17574+1021, a new DZA star identified in our survey. For stars without Hα or in the absence of spectroscopic data in this region sample, the fits are performed at a fixed hydrogen abundance, determined from the quality of the fit to the H & K doublet, since the amount of hydrogen present in the atmosphere influences the strength of these lines. The predicted energy distributions and spectra agree well with the observations for all 13 stars, except for 12145+7822, for which it is impossible to reproduce the narrow calcium lines with helium-atmosphere models at the low inferred temperature of $T_{\text{eff}} \sim 4200$ K. This suggests that this star has a hydrogen-rich atmosphere instead, which should produce much narrower absorption lines due to lower atmospheric pressures. Because we do not have model atmospheres that cover the appropriate range of parameters to fit this star, we adopt a photometric solution based on pure hydrogen models (see Figure 11), since the presence of metals is not expected to affect the atmospheric structures of hydrogen-rich models.

3.3. Spectroscopic Analysis

3.3.1. Spectroscopic Analysis of DA Stars

The atmospheric parameters of DA stars with well-defined Balmer lines ($T_{\text{eff}} \gtrsim 6500$ K) can be accurately determined from the optical spectra using the so-called spectroscopic technique pioneered by Bergeron et al. (1992, see also Liebert et al. 2005). The optical spectrum of each star, as well as all model spectra (convolved with a Gaussian instrumental profile), are first normalized to a continuum set to unity. The calculation of $\chi^2$ is then carried out in terms of these normalized line profiles only. The atmospheric parameters—
$T_{\text{eff}}$ and $\log g$—are considered free parameters in the fitting procedure. Since two solutions exist for a given star, one on each side of the maximum strength of the Balmer lines, we take advantage of our photometry to resolve the ambiguity. Also, since most of our spectra cover H, we include this line in our fitting procedure, allowing us to extend our spectroscopic fits down to $T_{\text{eff}} \sim 6100$ K, when H is available. However, we find that the internal errors on $\log g$ increase significantly for stars cooler than $T_{\text{eff}} < 6300$ K—and in particular for spectra with low S/N ($\text{S/N} < 40$)—reaching a spread of values as large as $\sigma_{\log g} \sim 0.3$ dex, while for the best spectra $\sigma_{\log g}$ can be as low as 0.04. In such cases where the internal errors become too large, $\log g$ is fixed at 8.0 and the uncertainty is set at 0.25 dex, which corresponds to a $\sim 2\sigma$ dispersion of the surface gravity distribution of hot DA stars (Gianninas et al. 2011).

Spectroscopic fits for 158 new DA stars identified in our survey, which can be analyzed with the spectroscopic technique, are presented in Figure 14. It is worth mentioning that 05025+5401 and 07029+4406 have atmospheric parameters placing them within the ZZ Ceti instability strip, and that periodic light variations are confirmed by observations that are presented along with the dominant pulsation periods in Green et al. (2015). Special care needs to be taken in the case of DA stars with unresolved M dwarf components, in order to reduce the contamination from the companion. When the contamination affects only H/3 and/or H/7, we simply exclude these lines from the fit, as indicated in Figure 14 by the green lines. At other times, emission lines from the M dwarf are also observed in the center of some Balmer lines (see, e.g., 13096+6933), in which case we simply exclude the line centers from our fitting procedure. A similar approach is adopted when the contribution from the M dwarf is large enough to fill up the Balmer line cores, resulting in predicted lines that are too deep (see, e.g., 04586+6209). However, as discussed in Section 3.2.2, the white dwarf spectrum is sometimes too contaminated by the M dwarf companion to be fitted with the spectroscopic technique (03031+2317, 04032+2520 E, and 08184+6606), and we must therefore rely on the photometric technique alone for these stars. Note that 04389+6351 was classified as a single DA star in Paper I, but we now find us from our fits that the predicted H/3 is too deep, suggesting that a red dwarf companion is filling the line (H/3 is actually excluded from our fit here). Our photometric fit for this star (not shown here) shows a significant infrared excess at $I_N$ and $JHK_S$, also suggesting the presence of a companion. We thus reclassify this star as a DA + M dwarf binary system.

There are also a few DAZ stars in our sample (including our new DAZ identifications 05431+3637, 14106+4075, and 22267+1753), for which the calcium H line (at 3968 Å) is blended with He. Since the upper Balmer lines are particularly sensitive to surface gravity, it is important to properly model the calcium lines for these stars. To do so, we relied on a small grid of synthetic spectra, based on our grid of pure hydrogen models, where calcium lines have been included in the calculation of the synthetic spectrum only (see Gianninas et al. 2011 and references therein). This grid covers a range in $T_{\text{eff}}$ from 6000 to 9000 K in steps of 500 K, $\log g$ from 7.0 to

**Figure 8.**(u-g, g-r) color–color diagram showing all stars in our survey for which ugriz photometry is available. The 151 spectroscopically confirmed white dwarfs are shown with various black symbols explained in the legend, while the 125 white dwarf candidates still lacking spectroscopic data are shown with red dots. The solid curves represent pure hydrogen model atmospheres at $\log g = 7.0, 8.0, \text{and} 9.0$ (from bottom to top); effective temperatures are indicated in units of $10^3$ K. The dashed curve corresponds to pure helium atmospheres at $\log g = 8.0$, and the dotted lines represent DQ models for 5 different compositions, from $\log C/He = 7.0, 8.0, \text{and} 9.0$.

**Figure 9.** Upper panel: equal cylindrical projection of the equatorial coordinates for the sample of white dwarfs identified from SUPERBLINK. The 416 previously known stars from the WD Catalog recovered by our selection criteria (open circles) are compared to the 325 new WD identifications (solid circles). Also shown by the bold solid line is the region of the galactic plane. Lower panel: sky density as a function of R.A., which corresponds to a color diagram showing all stars in our survey for selection criteria. It is worth mentioning that periodic light variations are confirmed by observations that are presented along with the dominant pulsation periods in Green et al. 2015 August.
9.5 in steps of 0.5 dex, and log Ca/H from −7.0 to −9.5 in steps of 0.5 dex.

### 3.3.2. Spectroscopic Analysis of DB Stars

For the analysis of the DB and DBA white dwarfs in our sample, we rely on the spectroscopic technique described at length in Bergeron et al. (2011), which is similar to that used for DA stars but modified to fit simultaneously $T_{\text{eff}}$, log $g$, and H/He. The first step is to normalize the flux from individual predefined wavelength segments, in both observed and model spectra, to a continuum set to unity. The comparison with model spectra, which are convolved with the appropriate Gaussian instrumental profile, is then carried out in terms of

![Sample fits to the photometric energy distributions (represented by error bars) of five new white dwarf identifications with pure hydrogen models (filled circles) and with pure helium models (open circles). The adopted solution is indicated in red. In the right panels are shown the observed normalized spectra together with the synthetic line profiles calculated with the atmospheric parameters corresponding to the pure hydrogen solutions.](image)

**Figure 10.** Sample fits to the photometric energy distributions (represented by error bars) of five new white dwarf identifications with pure hydrogen models (filled circles) and with pure helium models (open circles). The adopted solution is indicated in red. In the right panels are shown the observed normalized spectra together with the synthetic line profiles calculated with the atmospheric parameters corresponding to the pure hydrogen solutions.
this normalized spectrum only. However, as for DA stars, two solutions exist for a given DB spectrum, one on each side of the maximum strength of the neutral helium lines. Fortunately, all DB stars in our sample are relatively cool and it is easy to distinguish the cool and hot solutions from an examination of our best fits. Furthermore, the hydrogen abundance in DBA stars is better constrained if spectroscopic data near Hα are available, which is the case for most of our DB stars.

The spectroscopic fits for the 4 DB white dwarfs identified in our survey, of which 2 are DBA stars, are presented in Figure 15. Note that the hydrogen abundances in 12430+2057 represent only upper limits based on the absence of Hα.
3.4. Unresolved Double Degenerate Binaries

Four objects in Figure 11—04263+4820, 11337+6243, 11598+0007, and 14278+0532—show a predicted Hα absorption feature significantly deeper than the observed profile; these are plotted separately in Figure 16 for clarity. Note that 14278+0532 (1425+057) was fitted as a helium-rich DC white dwarf in Sayres et al. (2012) based on a noisy SDSS spectrum, but we clearly detect the Hα feature in our spectrum (see also Limoges et al. 2010). For all stars, we achieve excellent fits of the model spectral energy distributions to the photometry, but the fits to the observed spectra are poor. We experimented with helium-
rich models containing traces of hydrogen instead of pure hydrogen models (see, e.g., L745-46A and Ross 640 shown in Figure 14 of Giammichele et al. 2012). For 11337+6243 and 14278+0532, our best fits to these stars (not shown here) predict Hα profiles that are much broader than the observed profiles due to van der Waals broadening of hydrogen lines by neutral helium. The sharp features observed here rather suggest that these correspond to DA stars whose Hα absorption lines are diluted by the presence of an unresolved DC white dwarf companion. While it was possible to reproduce the Hα profile for 04263+4820 using helium-rich models, our best solution predicts a steep Balmer decrement due to the destruction of the

Figure 13. Fits to the energy distributions for the new DZ identifications. The filled circles correspond to our best fit with the atmospheric parameters given in each panel. In the right panels are shown the observed spectra together with the predicted model fit (in red); the insert shows our fit to Hα, when detected.
high atomic levels of hydrogen, in sharp contrast with the optical spectrum which shows the whole Balmer series all the way to H\(_\text{\epsilon}\). Here again we suggest that we are rather dealing with an unresolved DA+DC degenerate binary.

For 11598+0007, although the discrepancy observed in Figure 16 is not as extreme as for the other three objects, further evidence that we are also dealing with an unresolved binary is provided by the spectroscopic fit, displayed in Figure 17. Also shown for comparison is our best spectroscopic fit to 04263+4820, discussed above, and SDSS 1257+5428, a double white dwarf binary (DA + DA) discussed in Badenes et al. (2009), Kulkarni & van Kerkwijk (2010), and Marsh et al. (2011), of which the optical spectrum has been kindly provided to us by M. H. van Kerkwijk and S. R. Kulkarni. Not only is the spectroscopic temperature for 11598+0007 (\(T_{\text{eff}} \sim 7900\) K) significantly different from the photometric
temperature (∼9700 K), but the quality of the fit is poor, not unlike our best fit to SDSS 1257+5428 under the assumption of a single DA star. In addition, the hydrogen lines in 11598+0007 exhibit a strong asymmetry similar to that observed in Figure 1 of Kulkarni & van Kerkwijk (2010) for SDSS 1257+5428, attributed in this case to orbital motion and differences in gravitational redshift from both components of the binary system. Kulkarni & van Kerkwijk obtained $T_{\text{eff}} = 6250$ K and $\log g = 6.0$ for the primary, and $T_{\text{eff}} = 13,000$ K and $\log g = 8.5$ for the secondary; Marsh et al. (2011) obtained slightly different parameters but the basic suggestion of a cool, low-mass primary with a hotter, high-mass secondary remains the same. We thus suggest that 11598+0007 also represents an unresolved DA + DA double degenerate system. As demonstrated by Liebert et al. (1991), it is normally impossible to infer the presence of such DA + DA binary systems using the spectroscopic technique alone since the coaddition of synthetic spectra of two DA stars with different values of $T_{\text{eff}}$ and $\log g$ can be reproduced almost perfectly by a single DA spectrum unless the surface gravities of both components differ significantly, which is certainly the case for SDSS 1257+5428, and it is thus most probably the case for 11598+0007 as well. Finally, the similarity between our best spectroscopic fits to 11598+0007 and 04263+4820, both displayed in Figure 17, clearly suggests the same interpretation, although in the latter case, there is no obvious asymmetry in the line profiles, either because there is no velocity difference between both components of the system, or perhaps 04263+4820 is composed of a DA + DC system.

We do not attempt here to deconvolve the individual components of these double white dwarf binary candidates, and we simply adopt the effective temperatures from the photometric fits, which are more reliable than those derived from the line profiles. We further assume that both components have identical effective temperatures and surface gravities, and thus that they contribute equally to the total luminosity of the system, resulting in distances that are a factor of $\sqrt{2}$ larger than the values obtained under the assumption of a single white dwarf. These binaries will also contribute as two objects for the calculations of the luminosity function and the space density. A more detailed analysis of these double degenerate binaries will be presented elsewhere.

3.5. Known White Dwarfs within 40 pc of the Sun

In order to get a full picture of the physical properties of white dwarfs within 40 pc of the Sun, we must also include, in addition to the new white dwarfs identified in our survey, all previously known white dwarfs suspected to lie within 40 pc of the Sun. Our selection criteria applied to the SUPERBLINK catalog recovered a total of 416 known white dwarfs with $D_{\text{phot}} < 55$ pc. We reexamine this subset to exclude from the lot the known white dwarfs with distances well beyond 40 pc. This we do based on (1) a more robust photometric distance estimate described in Section 3.6, and (2) reliable
Figure 14. Fits to the optical spectra of the DA stars in our sample. The lines range from either Hα (when available) or Hβ (bottom) to H8 (top), each offset vertically by a factor of 0.2. Theoretical line profiles shown in green are not used in the fitting procedure.

(An extended version of this figure is available.)
spectroscopic distances found in the literature. We find 116 relatively distant white dwarfs, which leaves 300 white dwarfs that need to be included in our model atmosphere analysis, and for which optical spectra are thus required. Fortunately we already had spectra for 208 objects in this list, acquired over the years for various independent projects. Spectra for another 12 stars were directly available from the SDSS database. Also, optical spectra for 46 additional white dwarfs hot enough to be analyzed with the spectroscopic technique were secured during the spectroscopic observation campaigns listed in Table 1. Among these, GD 338 listed as a WD candidate by Giclas et al. (1980), turned out to be an MS star, thus reducing the number of known nearby white dwarfs to 299. Finally, 34 white dwarfs on our list are classified in the literature as DC or very cool DA stars, subtypes that can only be analyzed using the photometric technique, and for which we did not obtain new optical spectra because only a spectral type is sufficient for our present purposes.

We also need to include all known white dwarfs suspected to lie within ∼40 pc of the Sun but that were missed in our search of the SUPERBLINK catalog, either because they failed our selection criteria or are missing from the SUPERBLINK catalog itself for any reason. As discussed in Paper I, about 20% of the nearby white dwarfs are likely to be missed in our search because of their unusual photometry, in particular Sirius-like systems of white dwarfs companions to main-sequence stars. With this limitation in mind, we searched the following papers for objects with parallaxes larger than 0.025 yr⁻¹ or photometric/spectroscopic distances less than 40 pc of the Sun: the WD Catalog, Bergeron et al. (1997, 2001), Kawka & Vennes (2006), Kilic et al. (2006, 2010, 2012), Gatewood & Coban (2009), Sayres et al. (2012), Giammichele et al. (2012), Harris et al. (2013), Gianninas et al. (2015), as well as the large spectroscopic samples of Gianninas et al. (2011) and Genest-Beaulieu & Bergeron (2014, SDSS DR7) for DA stars, and Bergeron et al. (2011) for DB stars, and also Holberg et al. (2013) for Sirius-like systems. We also included individual objects such as the ultracool white dwarfs LHS 3250 (Harris et al. 1999; Bergeron & Leggett 2002), WD 0343+247 (Hambly et al. 1999), and SDSS J1102+4113 (Hall et al. 2008). Finally, we also searched nearby DZ stars in the sample of Dufour et al. (2007) and nearby DQ stars in the samples of Dufour et al. (2005) and Koester & Knist (2006), although we did not do a thorough search of the latest data releases of the SDSS. As was the case for the 20 pc sample, identifying all known white dwarfs with 40 pc of the Sun is a major endeavor, and we do not pretend that the above list is complete, especially given the large number of white dwarfs continuously being identified in the SDSS.

All these known white dwarfs suspected to lie within 40 pc of the Sun, within the uncertainties, have been combined with the 325 new white dwarfs identified in our survey of SUPERBLINK. We performed a spectroscopic or photometric analysis of each known white dwarf following the same fitting procedures described above. Since most of these stars have already been analyzed elsewhere in the literature, we do not provide here the detailed fits for individual stars, although our atmospheric parameters may reflect improved data sets and/or model spectra. We discuss some specific cases in turn.

As pointed out in Bergeron et al. (2011), several DB stars cooler than Teff ∼ 15,000 K show masses in excess of 1 M⊙, most likely because these cool objects, with their weak and shallow line profiles, lie at the limit of reliability for the spectroscopic technique. Three of these DB stars (KUV 02499+3442, 21003+3426, and 21499+2816) are in our sample of nearby candidates. Since the spectroscopic log g values and inferred distances are uncertain, we adopt log g = 8.0 for these
3 white dwarfs. Doing so, we obtain for 21499+2816 a distance of $37.7 \pm 1.5$ pc, in better agreement with the value of $35.3 \pm 3.8$ pc suggested by the trigonometric parallax. As mentioned in Bergeron et al., a value of $\log g = 8.2$ would actually reconcile both distance estimates perfectly, which suggests that the spectroscopic $\log g$ values for these stars are likely overestimated.

An interesting object in our sample is 09487+2421 ([0945+245], LB 11146), an unresolved binary system composed of a DA star and a magnetic white dwarf (DA + DAXP). We use here the values from Liebert et al. (1993) obtained by the deconvolution of both spectra: $T_{\text{eff}} = 11,500 \pm 300$ K, log H/He = $-2.89 \pm 0.3$, and log Ca/He = $-8.7 \pm 0.2$ under the assumption of $\log g = 8.0$. Since this last assumption will affect the spectroscopic distance estimate, we analyzed this star ourselves using the same spectroscopic technique for DB stars outlined in Section 3.3.2, with mixed H/He model atmospheres that also include the opacity from Ca II H & K; the additional lines of Mg and Fe visible in the spectrum are not included in our models. Our best fit is displayed in Figure 18 where we find $T_{\text{eff}} = 10,420$ K and $\log g = 7.71$; these are the only two free parameters in our fit. The helium abundance is set according to the depth of the HeI 5875 line reported by Koester et al. (2005), while the calcium abundance is fixed at a value that reproduces the observed strength of the calcium lines in our spectrum. The values we obtain for the helium abundance

Another interesting object in our sample is 01489+1902 (GD 16), a helium-rich DAZB star analyzed in detail by Koester et al. (2005). They obtained $T_{\text{eff}} = 11,500 \pm 300$ K, log H/He = $-2.89 \pm 0.3$, and log Ca/He = $-8.7 \pm 0.2$ under the assumption of $\log g = 8.0$. Since this last assumption will affect the spectroscopic distance estimate, we analyzed this star ourselves using the same spectroscopic technique for DB stars outlined in Section 3.3.2, with mixed H/He model atmospheres that also include the opacity from Ca II H & K; the additional lines of Mg and Fe visible in the spectrum are not included in our models. Our best fit is displayed in Figure 18 where we find $T_{\text{eff}} = 10,420$ K and $\log g = 7.71$; these are the only two free parameters in our fit. The helium abundance is set according to the depth of the HeI 5875 line reported by Koester et al. (2005), while the calcium abundance is fixed at a value that reproduces the observed strength of the calcium lines in our spectrum. The values we obtain for the helium abundance
(log H/He = −2.70), and for the calcium abundance (log Ca/He = −8.5), are in good agreement with the values derived by Koester et al. (2005), while the effective temperature is ~1100 K lower, a difference that may be explained by the fact that we do fit log g instead of simply assuming a value of 8.0. The corresponding distance of $D = 63.7 \pm 2.9$ pc is 13.7 pc farther away than the distance obtained by Koester et al., and significantly outside our limit of 40 pc. Finally, we notice that our spectrum displayed in Figure 18 shows what appears to be a blue component in the wings of H$\beta$, H$\gamma$, and H$\delta$, which could indicate that this object is in fact an unresolved double degenerate binary.

3.6. Adopted Atmospheric Parameters

As discussed in the Introduction, the spectroscopic log g values of DA stars show a significant increase at low temperatures ($T_{\text{eff}} \lesssim 13,000$ K) with respect to the log g distribution of hotter DA stars—the so-called high-log g problem. Hydrodynamical 3D models (Tremblay et al. 2013b see also Tremblay et al. 2011, 2013a) have now successfully shown that this problem is related to the limitations of the mixing-length theory used to describe the convective energy transport in standard 1D model atmospheres calculations. These spurious log g values prevent us from obtaining reliable mass and distance estimates for DA stars in our sample in this particular range of temperature. Indeed, those higher log g values will yield underestimated spectroscopic distances, biasing our census of white dwarfs within 40 pc. To overcome this problem, Giammichele et al. (2012) derived an empirical procedure (see their Section 5 and Figure 16) to correct the log g values based on the DA stars in the SDSS (DR4), analyzed by Tremblay et al. (2011); this was also our approach in Paper I. Here we make use of the latest results from Tremblay et al. (2013b) who presented their first complete grid of 3D synthetic spectra for DA white dwarfs based on 3D hydrodynamical model atmospheres. In particular, they provided correction functions to be applied to both $T_{\text{eff}}$ and log g measurements determined using the spectroscopic technique with model spectra calculated within the mixing-length theory—the ML2/$\alpha = 0.7$ prescription in our case. We thus apply these corrections to our sample of DA stars whose atmospheric parameters have been obtained using the spectroscopic method.

Because the distance to each white dwarf in our sample is a key issue in our study, some care must be taken to reduce the uncertainty on the distance estimates as much as possible. For stars with trigonometric parallax measurements available (167 objects), we adopt the corresponding distances directly. Out of these 167 parallax measurements, 9 have uncertainties larger than 20%, while Feige 4 and HZ 9 have uncertainties of 31% and 30%, respectively. However, even for these last two objects we prefer to use the parallax-based distances because the spectroscopic distance to Feige 4 is largely inconsistent with the parallax value (Bergeron et al. 2011), and because HZ 9 is a DA + M dwarf system whose spectral energy distribution is highly contaminated by the M dwarf, which means we only have a single data point to determine the distance from the photometric fit. For stars without parallaxes and fitted using the photometric method (DC, DQ, DZ, and cool DA stars), the
Table 4

| PM I       | ST  | $T_{\text{eff}}$ (K) | log $g$ | $M/M_\odot$ | Comp. | $M_V$ | log $L/L_\odot$ | $D$ (pc) | log $\tau$ | Fit$^a$ | Other name$^b$ |
|------------|-----|----------------------|--------|-------------|-------|-------|-----------------|----------|------------|--------|----------------|
| 00023+6357 | DC  | 4630 (563)           | 8.00 (0.25) | 0.58 (0.15) | H     | 14.77 | −4.18          | 26.7 (5.2) | 9.85       | 2      | ...           |
| 00050+4003 | DZA | 6150 (549)           | 8.00 (0.25) | 0.58 (0.15) | He    | 12.50 | −3.20          | 52.2 (9.4) | 9.05       | 2      | GD 1          |
| 00056+4825 | DA  | 6970 (105)           | 7.95 (0.09) | 0.56 (0.05) | He    | 13.47 | −3.45          | 48.4 (1.3) | 9.15       | 1      | ...           |
| 00074+3403 | DC  | 5830 (113)           | 8.00 (0.25) | 0.57 (0.15) | He    | 14.23 | −3.73          | 42.0 (5.2) | 9.46       | 2      | ...           |
| 00079+3947 | DC  | 4890 (453)           | 8.00 (0.25) | 0.58 (0.15) | He    | 15.16 | −4.09          | 20.2 (3.0) | 9.79       | 2      | ...           |
| 00217+2640 | DC  | 5160 (645)           | 8.00 (0.25) | 0.58 (0.15) | H     | 14.67 | −3.99          | 35.2 (6.1) | 9.69       | 2      | ...           |
| 00276+0542 | DA  | 5520 (855)           | 8.00 (0.25) | 0.58 (0.15) | H     | 14.65 | −3.87          | 21.5 (3.7) | 9.49       | 2      | ...           |
| 00331+4742 S | DA  | 16580 (265)          | 8.02 (0.05) | 0.63 (0.03) | H     | 11.13 | −1.95          | 55.0 (1.6) | 8.17       | 1      | ...           |
| 00334+2506 | DA  | 6310 (107)           | 7.89 (0.16) | 0.52 (0.09) | H     | 13.81 | −3.58          | 42.1 (0.8) | 9.22       | 1      | ...           |

Notes.

$^a$ Fit: (1) spectroscopic, (2) photometric.

$^b$ SDSS name unless noted otherwise.

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

distance is determined from the measured solid angle $\pi(RD)^2$ combined with the stellar radius corresponding to log $g = 8.0 \pm 0.25$, as discussed in Section 3.2.1. Finally, for white dwarfs in our sample only fitted with the spectroscopic technique and without parallaxes, we fit all the available photometric data but force the spectroscopic values of $T_{\text{eff}}$ and log $g$ (and the corresponding radius) and derive the distance from the fitted solid angle (see also Limoges et al. 2013). The distance uncertainty in this case is obtained from the combination in quadrature of the errors on the spectroscopic log $g$ and the solid angle. This approach for measuring spectroscopic distances has the advantage of using all the photometric information rather than relying on the distance modulus from a single bandpass.

Our final results for the 325 white dwarfs identified in our survey are presented in Table 4, while the results for the 492 white dwarfs, or white dwarf systems, identified within 40 pc of the Sun with $\delta > 0$ are presented in Table 5, which includes 178 new objects from our survey. Note that Table 5 includes several unresolved double degenerate systems (noted in the table). We give for each object the PM I designation if the white dwarf is a SUPERBLINK object, the spectral type, effective temperature ($T_{\text{eff}}$), surface gravity (log $g$), stellar mass ($M/M_\odot$), atmospheric composition (H- or He-dominated), absolute visual magnitude ($M_V$), luminosity ($L/L_\odot$), distance ($D$), trigonometric parallax (log $\tau$), and the method used to determine the atmospheric parameters. As discussed above, the spectroscopic solutions for both $T_{\text{eff}}$ and log $g$ for the DA stars have been corrected for the high-log $g$ problem and these differ from the uncorrected values given in Figure 14.

4. PHYSICAL PROPERTIES OF THE 40 pc SAMPLE

The atmospheric parameters of white dwarfs within 40 pc of the Sun given in Table 5 represent the end result of our large spectroscopic survey undertaken in 2009, and the foundation of the homogeneous study of the local white dwarf population presented below. Although not yet complete, this sample of 492 white dwarfs—or white dwarf systems—should be relatively free of kinematic bias, allowing us to draw a picture of the local white dwarf population (in the northern hemisphere) to a distance twice as large as the 20 pc sample analyzed by Holberg et al. (2008), Giammichele et al. (2012), and their predecessors. We provide in the following a detailed analysis of the physical properties of this sample, but we first attempt to evaluate the completeness of the sample in order to better understand its limitations.

4.1. Completeness of the 40 pc Sample

We compile 492 white dwarfs (501 including the double degenerate binaries) within 40 pc—to within the distance uncertainties—among which 178 are new identifications, marked with a star symbol in Table 5. Only 167 of these stars have trigonometric parallax measurements, however, and additional measurements in the near future (e.g., by the Gaia mission) will most likely add or remove stars from this sample. Until then, we can still evaluate the completeness of the 40 pc sample by calculating the cumulative number of stars as a function of distance. The results are displayed in Figure 19 where the cumulative number of stars in our sample is compared to the expected number of white dwarfs assuming a space density of $4.8 \times 10^{-3}$ pc$^{-3}$, which corresponds to the value derived from the smaller 13 pc sample, which is however believed to be complete (Holberg et al. 2008). The expected number of stars is also divided by a factor of two since our survey is restricted to the northern hemisphere. Also shown for comparison is the expected number of stars for the whole celestial sphere.

We first notice that within 20 pc, the cumulative number of stars reaches a value of 69, out of an expected number around 80 (or 85%), but the number of white dwarfs in our sample increases to 99 if we take into account the formal uncertainties in our distance measurements, stressing the importance of improving these distance estimates through precise trigonometric parallax measurements. Out of the 69 stars within 20 pc in our sample, 4 are new identifications (13413+0500, 14456+2527, 16325+0851, 23098+5506E), among which only 2 are actually fitted with the spectroscopic method allowing for more robust distance measurements, while for the other 2 objects, the distances are only estimated from the photometric method under the assumption of log $g = 8$. We also find 4 additional known white dwarfs within 20 pc with respect to the sample of Giammichele et al. (2012)—00222+4236, 11508+6831, 15350+1247, and 15425+2329. Hence, these results suggest that the 20 pc sample in the northern hemisphere is probably close to completeness, with a density consistent with the 13 pc sample.
| PM I  | ST  | $T_{\text{eff}}$ (K) | log $g$ | $M/M_\odot$ | Comp. | $M_V$ | log $L/L_\odot$ | $D$ (pc) | $\pi$ (mas) | log $\tau$ | Fit\(^a\) | WDname | Notes |
|-------|-----|---------------------|--------|-----------|-------|-------|---------------|--------|-----------|----------|----------|--------|-------|
| 00023+6357\(^b\) | DC  | 563 (63)           | 8.00 (0.25) | 0.58 (0.15) | H     | 14.77 | −4.18        | 26.7 (7.2) | ...       | 9.85     | 2       | ...    | ...   |
| 00051+7313 | DB  | 14490 (236)        | 8.34 (0.12) | 0.80 (0.08) | He    | 11.90 | −2.40        | 34.7 (5.8) | 28.8 (4.7) | 8.59     | 1       | 0002+729 | ...   |
| 00073+1230 | DC  | 5090 (65)          | 8.00 (0.25) | 0.57 (0.15) | He    | 14.62 | −4.02        | 21.0 (3.4) | ...       | 9.76     | 2       | 0004+122 | ...   |
| 00074+3403\(^b\) | DC: | 5830 (113)         | 8.00 (0.25) | 0.57 (0.15) | He    | 14.23 | −3.79        | 42.0 (7.3) | ...       | 9.46     | 2       | ...    | ...   |
| 00079+3947\(^b\) | DC  | 4890 (453)         | 8.00 (0.25) | 0.58 (0.15) | H     | 15.16 | −4.09        | 20.2 (4.2) | ...       | 9.79     | 2       | ...    | ...   |
| 00113+4240 | DA  | 7140 (106)         | 8.24 (0.07) | 0.75 (0.05) | H     | 13.80 | −3.56        | 19.3 (0.8) | ...       | 9.35     | 1       | 0008+424 | ...   |
| 00122+5025 | DAP | 6420 (99)          | 8.15 (0.10) | 0.68 (0.06) | H     | 14.09 | −3.69        | 11.0 (0.4) | 90.6 (3.7) | 9.42     | 1       | 0009+501 | ...   |
| 00136+0019 | DA  | 9520 (137)         | 7.97 (0.05) | 0.58 (0.03) | H     | 12.31 | −2.90        | 30.4 (4.5) | 32.9 (4.8) | 8.82     | 1       | 0011+000 | ...   |
| 00181+0029 | DB  | 18110 (288)        | 8.09 (0.06) | 0.65 (0.04) | He    | 10.99 | −1.86        | 33.3 (11.6) | 30.0 (9.4) | 8.12     | 1       | 0017+136 | ...   |

Notes. (1) Double degenerate binary (or candidate). (2) Gianninas et al. (2011). (3) $D$ from Vennes & Kawka (2012). (4) DXP+DA: $T_{\text{eff}}$, log $g$ and $D$ come from Liebert et al. (1993) and belong to the DA component; the values given for the companion are $T_{\text{eff}}=16,000 \pm 2000$ K and log $g=8.5 \pm 0.2$. (5) Trigonometric parallax from Dahn et al. (1982).

\(^a\) Fit: (1) spectroscopic, (2) photometric.

\(^b\) New WD identified in this survey.

(This table is available in its entirety in machine-readable form.)
Similarly, we find 125 white dwarfs within 25 pc (possibly up to 172 if we consider the distance uncertainties), whereas Sion et al. (2014) report a total of 224 white dwarfs for the same volume but in both hemispheres. Sion et al. estimate the completeness of their sample at 65%, which implies an expected number of white dwarfs around \(172\) in the northern hemisphere only, precisely the number we are finding if we allow for distance uncertainties. At 30 pc, the cumulative number of stars in Figure 19 becomes significantly less than expected (assuming that the space density of the 13 pc sample is valid everywhere), which suggests that our sample is significantly incomplete beyond this range.

By taking only the subsample of 427 stars with \(D < 40\) pc from Table 5, we derive a space density of \(3.19 \times 10^{-3}\) pc\(^{-3}\), with an upper estimate of \(3.74 \times 10^{-3}\) pc\(^{-3}\) if we take into account the distance uncertainties, which correspond to 66\%–78\% of the density of the 13 pc sample \((4.8 \times 10^{-3}\) pc\(^{-3}\)). Our upper estimate is thus consistent with the 77\% completeness value estimated in Paper I for the present efficiency of our survey in detecting white dwarfs using reduced proper motion diagrams. However, as mentioned in Section 2.2, \(\sim 330\) high-priority objects still remain to be observed out of our larger list of 1180 white dwarf candidates. Results from Paper I suggested that our discovery rate dropped to 54\% when stars that did not meet our best selection criteria (but with distance estimates less than 30 pc) were observed spectroscopically. Therefore, even if only 50\% of the remaining 330 high-priority candidates are confirmed as white dwarfs within 40 pc of the Sun, the number of such stars could rise to more than 600, which is the expected number of objects in Figure 19 based on the space density at 13 pc.

We must also consider the various sources of incompleteness in our survey that can prevent the identification of all white dwarfs within 40 pc of the Sun, especially those associated with

our use of the SUPERBLINK catalog as the primary source of candidates. First, our selection excludes stars fainter than \(V = 19\) since the rate of spurious detection in SUPERBLINK increases significantly at fainter magnitudes. Stars are also excluded if they have non-standard magnitudes for a white dwarf, a good example of which are Sirius-like systems, which are completely overlooked in our selected sample. In Sirius-like systems, as opposed to binary systems where the companion is an M dwarf, the flux is completely dominated by the MS star. In the 20 pc sample of Giannichele et al. (2012), there are 7 Sirius-like systems, all of which are in the southern hemisphere, with the exception of Procyon B \((0736+053)\), while in Holberg et al. (2013), there are 6 Sirius-like systems with \(D < 40\) pc in the northern hemisphere only. As expected, none of these were recovered by our selection criteria. We note, however, that 5 of these 6 systems were included in our analysis afterward; \(0911+023\) at 34.8 pc was let aside, however, since it is unresolved with a B star. The Sirius-like systems thus represent 3\% of the white dwarf population within 25 pc, and we may expect that \(\sim 13\) of these systems are missed in the 40 pc sample. Five other stars were missed because of their inaccurate colors, or because of a mismatch with SDSS and/or 2MASS magnitudes.

Some white dwarfs were also missed simply because they are not in the SUBERBLINK catalog to begin with. Stars with proper motions <40 mas yr\(^{-1}\) would of course not be part of our selection, but there are other cases where stars might be missing from the catalog. To be included in SUPERBLINK, a star must either be a TYCHO-2 or Hipparcos catalog stars, or it must be detected as a high proper motion star on the digitized POSS I and II plates. As discussed by Lépine & Shara (2005), SUPERBLINK is less efficient at recovering stars with bright saturated cores on those plates, leaving some bright stars out. Thus we note that some WD + M dwarf systems known to be within 40 pc were missed, in particular HZ 9, which is brighter than \(V = 13\) at \(I_V\). Sixteen very bright white dwarfs could also not be found in the published version of the SUPERBLINK catalog of Lépine & Shara (2005), and are thus also missing from our candidate list.

Finally, some stars can also be overlooked because of missing or inaccurate tabulated photometry in SUPERBLINK, most often due to faulty optical magnitudes from the USNO-B1.0 catalog counterpart. Because our selection criteria and distance estimates are based on empirical \(V\) magnitudes derived from USNO-B1.0 magnitudes, the estimated distances can be severely affected if the \(B_V\), \(R_V\), and \(I_V\) are inaccurate by more than the adopted 0.5 mag value. We actually identified 2 known white dwarfs that were not recovered in the USNO-B1.0 catalog, and 11 white dwarfs were also excluded from our candidate list because we estimated a distance larger than 55 pc. All in all, about 3\% of the stars are missed in this manner.

Taking into account all the sources of incompleteness, we estimate that, to the best of our knowledge, some 50 white dwarfs have probably been overlooked by our survey, for a ratio of missed-to-found of 17\%, a value consistent with the apparent 77\% efficiency of our survey at detecting white dwarfs, as discussed above. With these limitations in mind, we provide a detailed statistical analysis of our sample knowing that \(\sim 25\%\) of the white dwarfs might still be missing from our sample. Nevertheless, even if our 40 pc sample cannot be analyzed as thoroughly as the 20 pc sample, the small

![Figure 19](image_url) Cumulative number of stars as a function of distance, for our northern hemisphere census. The solid curve shows the expected number of white dwarfs in one hemisphere, assuming an average space density of \(4.8 \times 10^{-3}\) pc\(^{-3}\), while the dotted curve represents the expected number of white dwarfs on the whole celestial sphere.
number statistics problem inherent to the 20 pc sample discussed by Giammichele et al. (2012) has been significantly improved.

4.2. Kinematics of the 40 pc Sample

Before interpreting the global properties of the 40 pc sample, we must first verify if the sample is relatively free of kinematic bias, which we do by examining its velocity-space distribution. The velocity components \((U, V, W)\) are determined from the photometric distances (or trigonometric parallaxes when available) and proper motions for each star. Since radial velocities are not available for most of the stars in our sample, we assume \(V_{\text{rad}} = 0\), but in order to obtain an unbiased representation of the motion of the stars in our sample despite this approximation, we use the method described in Lépine et al. (2013). We first evaluate the \((X, Y, Z)\) positions of the stars in the Galactic reference frame and then we use the fact that \(U \propto (X/D)V_{\text{rad}}, \ V \propto (Y/D)V_{\text{rad}}\) and \(W \propto (Z/D)V_{\text{rad}}\) to obtain the \((U,V,W)\) velocity components. However, if \(|X| > |Y|\) and \(|X| > |Z|\), then the position vector as well as the radial velocity vector mainly points toward the X direction, so the radial velocity mainly contributes to the \(U\) component of velocity, but its contribution to the \(V\) and \(W\) components of velocity is small. Then, the \(V_{\text{rad}} = 0\) approximation is valid to obtain estimates for the velocity components \(V\) and \(W\), but not for \(U\). Likewise, stars with the largest \(\pm Y\) components (or \(\pm Z\) components) are good tracers of the velocity dispersion in \(U\) and \(W\) (or \(U\) and \(V\)), even if their radial velocities are not known. We can then estimate in this manner at least two velocity components for each star, and the component that depends the most on the radial velocity is excluded from any representation or statistical calculation.

Our results are displayed in Figure 20. For reasons outlined in the previous paragraph, each star appears in a single panel only. The mean values of the velocity components are

\[
\langle U \rangle = -9.82, \ \sigma_U = 41.00 \ \text{km s}^{-1},
\]

\[
\langle V \rangle = -26.58, \ \sigma_V = 29.46 \ \text{km s}^{-1},
\]

\[
\langle W \rangle = -8.26, \ \sigma_W = 17.37 \ \text{km s}^{-1},
\]

which happen to be in relative agreement with those reported by Fuchs et al. (2009) for stars in the SDSS belonging to the thin disk: \(\langle U \rangle = -8.6 \) and \(\sigma_U = 32.4 \ \text{km s}^{-1}\), \(\langle V \rangle = -20.0\) and \(\sigma_V = 23.0 \ \text{km s}^{-1}\), and \(\langle W \rangle = -7.1\) and \(\sigma_W = 18.1 \ \text{km s}^{-1}\). If we consider only the new white dwarf identifications (shown as solid circles in Figure 20), the space velocities we derive are of the same order, \(\langle U \rangle = -8.09\) and \(\sigma_U = 34.27 \ \text{km s}^{-1}\), \(\langle V \rangle = -23.98\) and \(\sigma_V = 27.87 \ \text{km s}^{-1}\), and \(\langle W \rangle = -6.85\) and \(\sigma_W = 19.31 \ \text{km s}^{-1}\), but we still notice the presence of “holes” in the distribution of new white dwarfs near \((U, W) = (0, 0)\) and \((U, V) = (0, 0)\) when compared to the velocity distribution of known white dwarfs. The red circle in each panel of Figure 20 represents the presumed kinematic limit of our survey due to the \(\mu > 0.04 \ \text{yr}^{-1}\) proper motion limit and \(D < 40 \ \text{pc} \) distance range, which corresponds to a transverse motion \(v_T = 4.74 \mu D = 7.6 \ \text{km s}^{-1}\). In Hipparcos, 2.3% of the stars fainter than \(V \sim 9\) with \(\delta > 0\) and \(\pi > 0.25 \ \text{yr}^{-1}\) \((D < 40 \ \text{pc})\) have \(\mu > 0.04 \ \text{yr}^{-1}\), implying that we are only missing \(\sim 11\) white dwarfs within \(40 \ \text{pc}\) because of the presumed kinematic limit of our survey. We also notice that the holes are larger than our presumed limit of detection, implying that some low-velocity white dwarfs are probably still hiding in our list of candidates, awaiting spectroscopic confirmation.

We find no white dwarfs in our 40 pc sample that appear reliably old enough to belong to the halo population of old stars. This is consistent with the Sion et al. (2014) study of the 25 pc sample, where no definite halo white dwarf was found either. Our only possible halo candidates are the two DC stars...
cool enough to be very old, however we cannot be certain of their age because we assumed log $g = 8.0$ by default for these stars, and an accurate cooling age can only be obtained when the stellar mass is known. Another possible candidate is the star 19401+8348, seen in the upper right corner of the ($U$, $W$) diagram in Figure 20, which has relatively high velocity components compared to the other stars in the diagram. This object is a DC star with $T_{\text{eff}} \approx 4800$ K and a distance of $D = 38.8 \pm 12$ pc, for which we also assumed log $g = 8.0$, which means its cooling age remains uncertain. Even if we extend our search to stars with $D > 40$ pc (not shown in Figure 20), we do not find any white dwarf that would reliably appear old enough to be a member of the halo population. This is, however, not inconsistent with the single-point luminosity function of Fontaine et al. (2001) based on the two halo white dwarfs 2316–064 and 1022+009, from which we estimate $n(L) = 10^{-5.39} \, \text{pc}^{-3} \, \text{M}_\odot^{-1}$ at log $L/L_\odot \sim -4.09$ ($T_{\text{eff}} \sim 5000$ K), which predicts the existence of only a single halo white dwarf within 40 pc of the Sun in this particular luminosity range. Finally, we note a small asymmetry in the two bottom panels of Figure 20 toward negative $V$ values, which might suggest a small but non-negligible component of the thick disk population in our sample.

4.3. Mass Distribution

The mass distribution for the white dwarfs in Table 5 with $D \lesssim 40$ pc is displayed in Figure 21 as a function of effective temperature. Only those with a measured mass are shown here (288 out of 492 objects from Table 5); the objects with an assumed value of log $g = 8.0$ are shown at the bottom of the figure. These include the coolest DA stars with weak hydrogen lines analyzed spectroscopically, most of the magnetic white dwarfs, and all non-DA stars analyzed photometrically but without trigonometric parallax measurements. Since most of our new identifications do not have trigonometric parallaxes available yet, the number of cool helium-rich white dwarfs with mass measurements is rather small in this figure, in comparison for instance with the mass distribution displayed in Figure 21 of Bergeron et al. (2001), which includes all cool white dwarfs with trigonometric parallax measurements available at that time. There, 54 out of 150 white dwarfs (or 36%) had helium-rich atmospheres, compared to 39 out 288 (or 13%) in Figure 21. In fact, most cool helium-atmosphere white dwarfs with mass determinations come from the 20 pc sample. The situation will of course change significantly when the Gaia mission is completed.

The cumulative mass distribution for the same subset of white dwarfs, regardless of their effective temperature, is displayed in Figure 22, where the separate contributions of hydrogen- and helium-rich stars are also shown. This distribution can be contrasted with that shown in Figure 21 of Giammichele et al. (2012) for the 20 pc sample. Here again we see that the helium-atmosphere white dwarfs in the 40 pc sample are significantly undersampled in the cumulative mass distribution. The relative number of helium- to hydrogen-rich objects in our sample is small, but we observe that the median masses and mass dispersions of both subsamples are generally comparable. The mean mass of the hydrogen-rich sample, however, is about 0.04 M$_\odot$ larger than the helium-rich counterpart. This is mostly due to the prominent high-mass tail observed in the distribution of hydrogen-atmosphere white dwarfs. To better illustrate this feature, we contrast in Figure 23 the mass distribution of the 40 pc sample with that of the 20 pc sample from Giammichele et al. (2012), which is based on both spectroscopic and photometric mass measurements, and with the spectroscopic mass distributions of DA stars from the SDSS (Tremblay et al. 2011) and from the WD Catalog (Gianninas et al. 2011). The excess of high-mass white dwarfs in the 40 pc sample is quite obvious, a result that strongly suggests we are
successfully recovering the high-mass, less luminous white dwarfs, which are often missed in magnitude-limited surveys (see, e.g., Liebert et al. 2005 in the case of the PG survey, and in particular their discussion of Figure 13). A higher fraction of massive white dwarfs has also been identified in the analyses of hot DA stars from ROSAT and Extreme-Ultraviolet Explorer (Vennes et al. 1996, 1997, 1998), since such surveys catalog all sources, regardless of the brightness of the object.

This excess of massive white dwarfs seems to be related to the population of low temperature white dwarfs apparent in Figure 21, between roughly $T_{\text{eff}} = 6000$ and 7000 K. These are all DA stars for which the atmospheric parameters—and in particular $\log g$ and thus $M$—have been determined spectroscopically. Note that even though 3D hydrodynamical corrections, which are negligible in this temperature range, have been properly applied to our spectroscopic results, it is still legitimate to question the validity of the spectroscopic masses in this particular range of temperature. As discussed in Tremblay et al. (2010)—see in particular their Figure 14 (panel b) and Section 5.1—the strength of the hydrogen lines in this temperature regime is particularly sensitive to the neutral particle interactions in the description of the occupation probability formalism, and a slight change in the hard sphere radius in this case may result in significantly lower $\log g$ values. Indeed, Bergeron et al. (1991) found that a direct implementation of the Hummer–Mihalas occupation probability formalism yields $\log g$ values that are too low in the regime where non-ideal effects become dominated by neutral interactions ($T_{\text{eff}} \lesssim 8000$ K), a problem that could be overcome by simply dividing the hydrogen radius by a factor of two to reduce the non-ideal effects for the higher lines of the Balmer series (this is the factor actually used in our models). At the same time, we also notice in Figure 21 that the mass distribution near $\sim 0.6 M_\odot$ in the same temperature range, and below, appears perfectly normal, suggesting that the model spectra are properly calibrated. Hence the high mass tail observed in Figure 22 might be real after all. Clearly, a detailed comparison of mass measurements derived from spectroscopy and precise trigonometric parallaxes in this range of temperature should shed some light on this result. Finally, we also note in Figure 21 an abrupt cutoff of massive white dwarfs below $\sim 6000$ K, but this is certainly due to the fact that cooler objects would appear as DC stars (or weak DA stars) whose masses can only be determined from the photometric method using trigonometric parallax measurements, which are currently unavailable. Hence it is possible that this high-mass tail extends to even lower temperatures.

Also superposed on the mass distribution shown in Figure 21 are the theoretical isochrones for our C/O core evolutionary models with thick hydrogen layers, as well as the corresponding isochrones with the MS lifetime taken into account; here we assume for simplicity (see Wood 1992) $\log M_\text{MS} = 10(M_{\text{MS}}/M_\odot)^{-2.5}$ Gyr and $M_{\text{MS}}/M_\odot = 8 \ln[(M_{\text{WD}}/M_\odot)/0.4]$. In the 20 pc sample of Giammichele et al. (2012), the 5 stars older than 8 Gyr (among which the oldest is 9.5 Gyr old) are all located in the southern hemisphere, and they are thus not included in our sample. The oldest white dwarf in Figure 21 is only $\sim 8$ Gyr old, although we see that there are plenty of objects without mass determinations that may be significantly older. The isochrones that include the MS lifetime reveal that white dwarfs with $M \lesssim 0.48 M_\odot$ cannot have C/O cores, and yet have been formed from single star evolution within the lifetime of the Galaxy. Some and probably all of the low-mass white dwarfs in Figure 21 must be unresolved double degenerate binaries with helium cores, i.e., the result of common envelope evolution. The known double degenerate systems are identified in Figure 21. Three of the low-mass ($M < 0.45 M_\odot$) white dwarfs with $\delta > 0$, 1345+238, 2048+263, and 2248+293, have already been discussed in Giammichele et al. (2012), while we identify here 01294+1023 (0126+101, DD, Bergeron et al. 2001), 03467+2456 (0343+247), 06026+0904, 09466+4354 (0943+441), 13309+3029 (1328+307, D2), 13455+4200, 15555+5025 (1546+505), 16540+6253 (1653+630; LHS 3250), 17055+4803 W (1704+481.2; Sanduleak B), 18205+1239 (1818+126, DD, Bergeron et al. 2001), 23253+1403 (2322+137), 22225+1221 (2220+121), and 23549+4027 (2352+401, DQ). Not surprisingly, most of these were already known in the literature since these objects, with their large radii and high luminosities, can easily be detected in most surveys.

The mean mass of the 40 pc sample (with mass determinations) is $\langle M \rangle = 0.699 M_\odot$ with a standard deviation of $\sigma_M = 0.185 M_\odot$. Figure 22. These values are significantly larger than those reported by Giammichele et al. (2012) for the 20 pc sample, $\langle M \rangle = 0.650 M_\odot$ and $\sigma_M = 0.161 M_\odot$. Our higher mean mass is actually due to the hydrogen-rich white dwarfs in the 40 pc sample, with $\langle M_{\text{H}} \rangle = 0.705 M_\odot$, while Giammichele et al. obtained $\langle M_{\text{H}} \rangle = 0.650 M_\odot$. However, the mean masses for the helium-atmosphere white dwarfs are identical, $\langle M_{\text{He}} \rangle = 0.660 M_\odot$, which also compare really well with the mean mass for DB stars determined spectroscopically by Bergeron et al. (2011), $\langle M_{\text{He}} \rangle = 0.671 M_\odot$. As mentioned above, the mass distribution of the 40 pc sample also peaks at larger mass values than the 20 pc sample, although it is
4.4. Evolution of Surface Composition

Since the photometric data set for the 40 pc sample is not as accurate as that of the 20 pc sample, it is not yet possible to study the evolution of the surface composition as a function of temperature in as much detail as in Bergeron et al. (1997, 2001), for instance (see also Bergeron et al. 2013). Also, since trigonometric parallax measurements are not available for most of the new white dwarfs identified in the 40 pc sample, stellar masses cannot be determined for these objects either. It is still possible, however, to examine the spectral evolution of the white dwarfs in our sample by ignoring this second parameter and by remembering that our temperature scale remains somewhat uncertain for some stars, in particular those that have only USNO-B1.0 photographic magnitudes available.

The distribution of the main spectral types (DA, DC, DQ, DB, and DZ) as a function of effective temperature is displayed in Figure 24; the only 2 white dwarfs missing from this figure are the DXP stars 17481+7052 (1748+708, G240–72) and 18303+5447 (1829+547, G227–35). We can see that, as expected, the local sample is dominated by cool white dwarfs (see also Figure 21), with the typical rise in the number of cool DA and DC stars—the dominant spectral types here—expected at the faint end of the luminosity function. We notice that the sudden drop in the number of DA stars below \( T_{\text{eff}} \approx 5000 \) K is largely compensated by the significant increase in the number of DC stars in the same temperature range, which suggests that several of these DC stars probably have hydrogen-rich atmospheres. Many of them might even reveal the presence of H\( \alpha \) when observed at even larger S/Ns using 4–10 m class telescopes, as demonstrated for instance by Greenstein (1986) or Bergeron et al. (1997).

While no DB stars were reported in the 20 pc sample studied by Giammichele et al. (2012), the 40 pc sample now includes 7 DB stars—00051+7313 (0002+729), Feige 4 (0017+136), KUV 05034+1445 (0503+147), GD 325 (1333+487), 16473+3228 (1645+325), 20123+2338 (2010+310) and 21499+2816 (2147+280)—and none of these correspond to new detections. DQ and DZ stars are rather rare in our sample, representing only 5% of all white dwarfs below \( T_{\text{eff}} \sim 12,000 \) K, but still 40% of all helium-atmosphere white dwarfs in the 6000–12,000 K temperature range (the spectral type alone below 6000 K is not sufficient to infer the chemical composition). While it is difficult to misclassify a DQ star in our sample, in particular at low temperatures where the C\(_2\) Swan bands are usually the strongest, a significant number of DZ stars might still be present among the 118 cool DC stars in our sample due to the lack of appropriate spectral coverage, resolution, or S/N of our spectroscopic observations.

As discussed in the Introduction, it is now believed that most if not all cool DC stars with \( T_{\text{eff}} \lesssim 5000 \) K probably have hydrogen-rich atmospheres, a result based on a re-analysis of the existing photometry with model atmospheres that include the red wing opacity from Ly\( \alpha \) (this excludes DQ and strong DZ stars in the same temperature range, which obviously have helium-dominated atmospheres). We have four DC white dwarfs below 5000 K in Figure 21 with helium atmospheres, two of which are known in the literature and only one with trigonometric parallax, and thus mass measurements. For some of these objects, we do not even have a spectrum near H\( \alpha \), and in some other cases the photometry is clearly suspicious, in particular at JHK. Hence for all four stars, the pure hydrogen solution would be equally acceptable. We thus reaffirm the conclusion first made by Kowalski & Saumon (2006), and supported by Giammichele et al. (2012), that most cool DC stars probably have hydrogen atmospheres.

One of the most puzzling results of our analysis is displayed in Figure 25 where we show in the left panel the total number of stars as a function of effective temperature per bin size of 2000 K, as well as the individual contribution of the hydrogen-atmosphere white dwarfs, while we show in the right panel the ratio of helium-atmosphere white dwarfs to the total number of stars. As mentioned in the previous paragraph, the results comparable to the peak value obtained by Gianninas et al. (2011) for the DA stars in the WD catalog of McCook & Sion, also reproduced in Figure 22.
below $T_{\text{eff}} = 5000$ K should be considered with caution. The results above this temperature, however, are fairly robust since most solutions are constrained by the presence or absence of Hα when the photometric method is used, or in the case of hotter DA stars, the atmospheric parameters have been obtained from the spectroscopic method. Above
15,000 K, the fraction of helium-atmosphere white dwarfs is around 25%, in good agreement with the fraction of DB stars found in the PG survey, as determined by Bergeron et al. (2011). In the 13,000–15,000 K temperature range, this fraction drops to only 5%, although the total number of helium-rich stars in this temperature bin is admittedly small (see the left panel). Below 13,000 K, the fraction of helium-atmosphere white dwarfs gradually increases toward lower temperatures, and keeps increasing to a ratio around ~25% in the 7000–9000 K temperature range. Even though this trend is entirely consistent with the results reported by Giammichele et al. (2012), see their Figure 20) for the 20 pc sample, the fraction of helium-atmosphere white dwarfs reaches a much higher value around 40% in the 20 pc sample. To better understand this discrepancy, we show in Figure 26 similar results as those displayed in Figure 25 but only for temperatures in the range 7000 > Teff > 9000 K and this time as a function of distance. Below 20 pc, we recover the results of Giammichele et al. (2012) almost perfectly, but beyond this distance, the fraction of helium-atmosphere white dwarfs drops abruptly. By looking at the results shown in the left panel of Figure 26, we can see that the 20 pc sample probably suffers from small number statistics, and that these statistics become more significant at larger distances. Otherwise, we cannot think of a single bias in our survey that would produce such a trend, either in favor of DA stars beyond 20 pc, or against non-DA stars. We thus believe that the peak value near 40% reported by Giammichele et al. was overestimated.

In Giammichele et al. (2012, see also Tremblay & Bergeron 2008), the increase in the fraction of helium-atmosphere white dwarfs at lower temperatures was interpreted as the result of convective mixing, where the thin convective hydrogen atmosphere is mixed with the deeper and more massive helium convection zone. Since the fraction of helium-atmosphere white dwarfs at low temperatures in our sample is now consistent with that of DB stars at higher temperatures (here and in the PG sample), there appears to be little evidence that convective mixing ever occurs in cool DA stars, at least in the temperature range considered here. This in turn implies that DA stars have fairly thick hydrogen layers of the order of M_H/M_\odot \sim 10^{-6} (see Figure 1 of Tremblay & Bergeron 2008). This revised conclusion is a direct consequence of our analysis of a more statistically significant, volume-limited sample.

Finally, as discussed in the Introduction, Bergeron et al. (1997, 2001) suggested the presence of a non-DA gap (or deficiency) between Teff \sim 5000 and 6000 K where most stars appear to have hydrogen-rich compositions, while helium-atmosphere white dwarfs exist above and below this temperature range (see also Bergeron et al. 2013). While we have indeed very few (~3) helium-atmosphere white dwarfs in Figure 21 with a mass determination in this particular range of temperature, our sample still contains a significant number of such helium-rich stars without mass determinations. However, as mentioned before, the photometric data for most of these objects are not accurate enough to pinpoint their temperature with sufficient precision, and we will thus refrain from further interpreting the presence or absence of this non-DA gap in our sample at this stage.

4.5. Luminosity Function

As discussed in the Introduction, one of the goals of our spectroscopic survey is to provide an improved determination of the cool end of the white dwarf luminosity function (WDLF), as statistically complete as possible, which can then be compared to those obtained from magnitude-limited surveys, from large photometric and spectroscopic surveys like the SDSS, or from the volume-limited sample of white dwarfs within 20 pc of the Sun. The WDLF is a measure of the number of stars per pc^3 per unit of bolometric magnitude, which can be obtained in our case using the bolometric magnitude of each white dwarf within 40 pc of the Sun and with $\delta > 0$ derived from the spectroscopic or photometric results provided in Table 5. The bolometric magnitudes can be obtained from the luminosity of each star given in the table (log L/L_\odot) and the simple relation $M_{bol} = -2.5 \log L/L_\odot + M_{bol}$, where $M_{bol} = 4.75$ is the bolometric magnitude of the Sun. We present here an observed luminosity function, in the sense that we do not attempt to apply any correction due to the incompleteness of our survey. Each object in the sample is then simply added to the appropriate bolometric magnitude bin, and the overall results are divided by the volume defined by a 40 pc half-sphere. Since the WDLF requires a proper account of the number of individual stars in each magnitude bin, the confirmed and suspected double degenerate binary systems are counted as two stars. Also, in order to obtain the most accurate mass density as possible, we deconvolve the individual masses of each system by using the procedure described in Section 6.4 of Giammichele et al. (2012). Doing so, our luminosity function now includes a total of 501 individual white dwarfs.
The luminosity function for the white dwarfs within 40 pc of the Sun is presented in Figure 27 (the approximate temperature scale for a $M = 0.6 M_{\odot}$ evolutionary sequence is shown at the top of the figure). Our results are also compared with those obtained by Giammichele et al. (2012) for the 20 pc sample, by Harris et al. (2006) for white dwarfs in the SDSS, and by Bergeron et al. (2011) for the DA and DB stars in the PG survey. In Figure 28 we reproduce the same luminosity function but in half-magnitude bins together with theoretical luminosity functions from Fontaine et al. (2001) for a total age of 10–12 Gyr, normalized to our own observational results between $M_{\text{bol}} = 12$–14. These were obtained, as explained in Fontaine et al. (2001), with a constant star formation rate (SFR), a classic Salpeter initial mass function (IMF, $\phi = M^{-2.35}$), an initial-to-final mass relation (IFR) given by $M_{\text{WD}} = 0.4 e^{0.125 M}$, and an MS lifetime law given by $t_{\text{MS}} = 10 M^{-2.5}$ Gyr ($M$ and $M_{\text{WD}}$ are in solar units). The half-magnitude bins have been selected to better match the peak of the theoretical luminosity functions.

If the SFR is constant, we expect a monotonous rise of the luminosity function, as shown by the theoretical curves in Figure 28. Alternative bursts in star formation would show up as bumps in the luminosity function (Noh & Scalo 1990). Our WDLF displayed in both Figures 27 and 28 shows a definite bump near $M_{\text{bol}} \sim 10$. A similar bump was also observed in the WDLF determined by Harris et al. (2006; see their Figures 4 and 8) for the SDSS sample and by Giammichele et al. (2012, see their Figure 22) for the 20 pc sample (both reproduced here in Figure 27), but this peculiar feature in Giammichele et al. had been attributed by the authors to small number statistics. Here we have more than tripled the number of stars in the magnitude bins of interest, and the result now appears to be statistically significant. The brightest magnitude bins have error bars that are still large enough to be consistent with the theoretical expectations, but the points at $M_{\text{bol}} = 10$ and 11 are solid determinations. This particular feature in the WDLF can also be observed directly in Figure 21 and in the left panel of Figure 25 and could be explained by a sudden burst of star formation in a recent past. A direct comparison of our results with the simulations shown in Figure 6 of Noh & Scalo (1990) suggests a burst of star formation that occurred about 0.3 Gyr ago, a conclusion also reached by Harris et al. (2006) based on the SDSS data. An alternative but less likely explanation would be that the luminosity function for $M_{\text{bol}} > 10$ is still very incomplete. Indeed, the drop in the space density near $M_{\text{bol}} = 11$ is also observed in the luminosity function of the PG sample, precisely in the region where the PG survey becomes incomplete. However, the number of stars missing in our survey would have to be enormous (Figures 27 and 28 use a logarithmic scale), an unlikely possibility given our estimate of the completeness of this survey. In Giammichele et al. (2012), this drop in the number of stars near $T_{\text{eff}} \sim 14,000$ K was also tentatively explained by the inaccurate treatment of convective energy transport in the models, since this corresponds to the temperature where the atmospheres of DA stars become convective. However, since we applied here the appropriate 3D to 1D hydrodynamical corrections from Tremblay et al. (2013b), this explanation can be ruled out.

As expected, the WDLF displayed in Figure 27 shows that our survey samples the cool end of the luminosity function really well, with a significant number of stars in each magnitude bin, as opposed to the color-excess PG survey for instance. Our derived space density is consistent with that obtained by Harris et al. (2006) for white dwarfs in the SDSS, except near the peak region, but again, our results have not been corrected for incompleteness. At the same time, there are significant corrections applied to the SDSS sample in this particular range of luminosities, all of which remain extremely uncertain. Note also that the number of stars in the fainter magnitude bins of our WDLF must be considered with caution, since for most cool white dwarfs in our sample, we had to assume a value of $\log g = 8.0$ due to the lack of trigonometric parallax measurements. Hence a change in $\log g$ values could shift some stars from one bin to the other. As a matter of fact, the mean mass of our sample is actually closer to $0.7 M_{\odot}$ rather than the $0.6 M_{\odot}$ assumed here for those stars. A larger average mass would imply smaller radii and lower luminosities, thus shifting the stars to fainter magnitude bins in both Figures 27 and 28. Precise parallax measurements, like those that will become available from the Gaia mission, will be required to improve the shape of the WDLF at low luminosities, in particular since only the last magnitude bin is sensitive to the age of the galactic disk. Despite these uncertainties, we can still conclude that our results are consistent with an age of the galactic disk around 11 Gyr.

Our WDLF displayed in Figure 28 also fails to reproduce the peak of the theoretical luminosity functions near $M_{\text{bol}} \sim 15$, despite the finer resolution used in this plot. This pronounced peak or bump in the theoretical luminosity functions has been discussed in detail by Fontaine et al. (2001, see their Figures 5 and 6), who attribute this feature to the combined signatures of
both convective coupling and crystallization, although the contribution of the latter process is significantly less than that of the former since the release of latent heat operates over a wide range of luminosities. Consequently, its effects tend to be averaged out over that luminosity interval. Given the size of the error bars of our observed WDLF in this particular region of bolometric magnitudes, it is unlikely that our white dwarf sample misses so many objects. The most likely explanation is that the assumptions built into the construction of these theoretical luminosity functions mentioned above (SFR, IMF, IFR, etc.) should perhaps be reexamined and explored further, particularly the simplistic IFR used in these calculations. Another aspect that would need to be explored quantitatively is the effect of an old thick disk component (see Section 4.2) on the predicted luminosity function, with a different scale height appropriate for this population.

Finally, by integrating the WDLF over all magnitude bins, it is possible to obtain a measure of the total space density of white dwarfs in our sample, which in turn can be used to evaluate the completeness of our survey. Holberg et al. (2008) obtained for the 13 pc sample, believed to be complete, a space density of $(4.8 \pm 0.5) \times 10^{-3} \text{pc}^{-3}$ and a mass density of $(3.2 \pm 0.3) \times 10^{-3} M_\odot \text{pc}^{-3}$. Using these numbers as a reference point, Giammichele et al. (2012) concluded that the 20 pc sample was 90% complete. For the 40 pc sample, we derive a space density of $3.74 \times 10^{-3} \text{pc}^{-3}$ and a corresponding mass density of $2.46 \times 10^{-3} M_\odot \text{pc}^{-3}$, which would imply that the 40 pc sample in the northern hemisphere is 78% complete, in agreement with our other estimates above.

5. CONCLUDING REMARKS

Our spectroscopic survey of white dwarfs within 40 pc of the Sun is not yet complete and there is still a significant amount of work to be done. First of all, we have a few high-priority targets in our sample, some of which are bright enough to be observed with 2 m class telescopes, while some faint targets around $V \sim 19$ will require large aperture telescopes, such as Gemini North or South. Among the brightest objects which could not be observed because of uncooperative weather, several candidates with $D < 30$ pc remain on our target list, as well as 5 Giclas objects: 01309+5321 (GD 278), 02011+1212 (GD 21), 07544+6611 (GD 454), 14065+7418 (GD 492), and 22022+3848 (GD 399). Also, the southern hemisphere should eventually be dealt with, but it is not clear how much effort should be put into this given the work of Sayres et al. (2012) for decl. close to $\delta = 0$, as well as the SOAR + SMARTS Southern White Dwarf SURVEY of Subasavage et al. (2009), which uncovered 100 new white dwarfs. The current homogeneity of white dwarf surveys within 20 pc of the Sun in both hemispheres is about to be extended to 25 pc in the near future, and eventually to larger distances. The ultimate confirmation of the white dwarfs identified in our survey as members of the 40 pc sample will of course come from precise trigonometric parallaxes from the Gaia mission. In addition to adding or removing stars from the 40 pc sample, these measurements will also help to better define the faint end of the luminosity function revealed by our survey.

We are grateful to the referee, Hugh C. Harris, for his detailed and constructive comments that have greatly helped improve the content and presentation of our results. We would like to thank the director and staff of Steward Observatory, Kitt Peak National Observatory, and the Observatoire du Mont-Mégantic for the use of their facilities, as well as the director and staff of Gemini North and South Observatories for the remote observing. We would also like to thank P. Dufour for making his DQ and DZ models available to us, G. Fontaine for the theoretical luminosity functions, and S.R. Kulikarni and M.H. van Kerkwijk for allowing us to use their spectrum of SDSS 1257+5428. This work was supported in part by the NSERC Canada and by the Fund FRQ-NT (Québec). S.L. was supported in this research by NSF grants AST 06-07757 and AST 09-08419. S.L. also acknowledges support from the GALEX Guest Investigator program under NASA grant NNX09AF88G. This research made use of the SIMBAD database and the VizieR catalog access tool, operated at CDS, Strasbourg, France, and also made use of 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 the National Aeronautics and Space Administration and the National Science Foundation.

REFERENCES

Adelman-McCarthy, J. K., Agüeros, M. A., Allam, S. S., et al. 2008, ApJS, 175, 297
Badenes, C., Mullally, F., Thompson, S. E., & Lupton, R. H. 2009, ApJ, 707, 971
Beauchamp, A., Wesemael, F., & Bergeron, P. 1997, ApJ, 482, 559
Bergeron, P., Dufour, P., & Giammichele, N. 2013, in ASP Conf. Ser. 469, 18th European White Dwarf Workshop, ed. J. Krzesinski, G. Stuchlowski, P. Moskalik, & K. Bajan (San Francisco, CA: ASP), 127
Bergeron, P., & Leggett, S. K. 2002, ApJ, 580, 1070
Bergeron, P., Leggett, S. K., & Ruiz, M. T. 2001, ApJ, 133, 413
Bergeron, P., Ruiz, M. T., & Leggett, S. K. 1997, ApJ, 108, 339
Bergeron, P., Saifer, R., & Liebert, J. 1992, ApJ, 394, 228
Bergeron, P., Saumon, D., & Wesemael, F. 1995, ApJ, 443, 764
Bergeron, P., Wesemael, F., Dufour, P., et al. 2011, ApJ, 737, 28
Bergeron, P., Wesemael, F., & Fontaine, G. 1991, ApJ, 367, 253
Bothlin, R. C., & Gilliland, R. L. 2004, AJ, 127, 3508
Chen, E. Y., & Hansen, B. M. S. 2011, MNRAS, 413, 2827
Chen, E. Y., & Hansen, B. M. S. 2012, ApJL, 753, L16
Cohen, M., Wheaton, W. A., & Megreath, S. T. 2003, AJ, 126, 1090
Dahn, C. C., Harrington, R. S., Riepe, B. Y., et al. 1982, AJ, 87, 419
Dufour, P., Bergeron, P., & Fontaine, G. 2005, ApJ, 627, 404
Dufour, P., Bergeron, P., Liebert, J., et al. 2007, ApJ, 663, 1291
Fontaine, G., Brassard, P., & Bergeron, P. 2001, PASP, 113, 409
Fuchs, B., Dethern, C., Rix, H.-W., et al. 2009, AJ, 137, 4149
Fukugita, M., Ichikawa, T., Gunn, J. E., et al. 1996, AJ, 111, 1748
Gatewood, G., & Cohen, L. 2009, AJ, 137, 402
Genest-Beaulieu, C., & Bergeron, P. 2014, ApJ, 796, 128
Giammichele, N., Bergeron, P., & Dufour, P. 2012, ApJS, 199, 29
Gianninas, A., Bergeron, P., & Ruiz, M. T. 2011, ApJ, 743, 138
Gianninas, A., Curt, B., Thorstensen, J. R., et al. 2015, MNRAS, 449, 3966
Giclas, H. L., Burnham, R. Jr., & Thomas, N. G. 1980, LowOB, 8, 157
Gil de Paz, A., Boissier, S., Madore, B. F., et al. 2014, AJ, 217, 30185
Green, E. M., Limoges, M.-M., Gianninas, A., et al. 2015, in ASP Conf. Ser. 493, 19th European Workshop on White Dwarfs, ed. P. Bergeron, & G. Fontaine (San Francisco, CA: ASP), 237
Green, R., Schmidt, M., & Liebert, J. 1986, ApJS, 61, 305
Greenstein, J. L. 1986, ApJ, 304, 334
Hall, P. B., Kowalski, P. M., Harris, H. C., et al. 2008, AJ, 136, 76
Hambly, N. C., Smartt, S. J., Hodgkin, S. T., et al. 1999, MNRAS, 309, L33
Harris, H. C., Dahn, C. C., Dupuy, T. J., et al. 2013, ApJ, 779, 21
Harris, H. C., Dahn, C. C., Vrba, F. J., et al. 1999, ApJ, 524, 1000
Harris, H. C., Munn, J. A., Kilic, M., et al. 2006, AJ, 131, 571
Heg, E., Fabricius, C., Makarov, V. V., et al. 2000, A&A, 355, L27
Holberg, J. B., & Bergeron, P. 2006, AJ, 132, 1221
Holberg, J. B., Oswalt, T. D., Sion, E. M., Barstow, M. A., & Burleigh, M. R. 2013, MNRAS, 435, 2077
Holberg, J. B., Sion, E. M., Oswalt, T., et al. 2008, AJ, 135, 1225
Holberg, J. B., Sion, E. M., & Oswalt, T. D. 2011, BAAS, 217, 341.02
Hummer, D. G., & Mihalas, D. 1988, ApJ, 331, 794
