A catalogue of white dwarf candidates in VST ATLAS

Nicola Pietro Gentile Fusillo,1* Roberto Raddi,1 Boris T. Gänsicke,1 J. J. Hermes,2† Anna F. Pala,1 Joshua T. Fuchs,2 Ben Chehade,3 Nigel Metcalfe3 and Tom Shanks3

1Department of Physics, University of Warwick, Coventry CV4 7AL, UK
2University of North Carolina, Chapel Hill, NC 27599-3255, USA
3Department of Physics, Durham University, South Road, Durham DH1 3LE, UK

Accepted 2017 March 24. Received 2017 March 23; in original form 2017 January 21

ABSTRACT
The Sloan Digital Sky Survey (SDSS) has created a knowledge gap between the Northern and the Southern hemispheres, which is very marked for white dwarfs: Only \( \lesssim 15 \) per cent of the known white dwarfs are south of the equator. Here, we make use of the VLT Survey Telescope (VST) ATLAS survey, one of the first surveys obtaining deep, optical, multiband photometry over a large area of the southern skies, to remedy this situation. Applying the colour and proper-motion selection developed in our previous work on SDSS to the most recent internal data release (2016 April 25) of VST ATLAS, we created a catalogue of \( \approx 4200 \) moderately bright \((g \leq 19)\), high-confidence southern white dwarf candidates, which can be followed up individually with both the large array of southern telescopes or in bulk with ESO’s forthcoming multi-object spectrograph 4MOST.

Key words: catalogues – surveys – proper motions – white dwarfs.

1 INTRODUCTION
White dwarfs are the final stage of the evolution of stars with main sequence masses \( M > 0.8 \) and \( M \lesssim 8-10 M_\odot \) (Iben, Ritossa & Garcia-Berro 1997), a range that includes the vast majority of all stars. White dwarfs are therefore key tracers of the evolutionary history of the Galaxy (e.g. Torres et al. 2005; Tremblay et al. 2014) and significant contributors to the global stellar population. However, to fully exploit the diagnostic potential of the Galactic white dwarf population, it is necessary to reliably constrain fundamental parameters such as their space density (Holberg, Oswalt & Sion 2002; Holberg et al. 2008; Giammichele, Bergeron & Dufour 2012; Sion et al. 2014), mass distribution (Bergeron, Saffer & Liebert 1992; Liebert, Bergeron & Holberg 2005; Falcon et al. 2010; Tremblay et al. 2013, 2016) and luminosity function (Catalán et al. 2008; Giammichele et al. 2012; Rebassa-Mansergas et al. 2015). These studies require large, homogeneous and well-defined samples that, given the intrinsic low luminosity of white dwarfs, are still challenging to be assembled.

Large samples of white dwarfs are also the starting point in searches for rare sub-types like magnetic white dwarfs (Gänsicke, Euchner & Jordan 2002; Schmidt et al. 2003; Külebi et al. 2009; Kepler et al. 2013; Hollands, Gänsicke & Koester 2015), pulsat- ing white dwarfs (Castanheira et al. 2004; Greiss et al. 2014; Gentile Fusillo, Hermes & Gänsicke 2016, see Section 6.4), high/low mass white dwarfs (Vennes & Kawka 2008; Brown et al. 2010; Hermes et al. 2014), white dwarfs with unresolved low mass companions (Farihi, Becklin & Zuckerman 2005; Girven et al. 2011; Steele et al. 2013), white dwarfs with rare atmospheric composition (Schmidt et al. 1999; Dufour et al. 2010; Gänsicke et al. 2010; Kepler, Koester & Ourique 2016), close white dwarf binaries (Marsh, Nelemans & Steeghs 2004; Parsons et al. 2011), metal polluted white dwarfs (Sion, Leckenby & Szkody 1990; Zuckerman & Reid 1998; Dufour et al. 2007; Koester, Gänsicke & Farihi 2014; Raddi et al. 2015) or white dwarfs with dusty or gaseous planetary debris discs (Gänsicke et al. 2006; Farihi, Jura & Zucker- man 2009; Debes et al. 2011; Wilson et al. 2014; Manser et al. 2016).

In recent years, the number of known white dwarfs has increased by an order of magnitude, in particular thanks to the Sloan Digital Sky Survey (SDSS, York et al. 2000) that led to the identification of over 26,000 white dwarfs mainly in the Northern hemisphere (Harris et al. 2003; Eisenstein et al. 2006; Kleinman et al. 2013; Kepler et al. 2015; Gentile Fusillo, Gänsicke & Greiss 2015a; Kepler et al. 2016). The Southern hemisphere (below Dec. \( \approx -20^\circ \)) has not yet been surveyed by deep multicolour CCD photometric surveys, and consequently only \( \approx 15 \) per cent of all known white dwarfs are south of the celestial equator (cf. Fig. 1). However, the potential for identifying large numbers of white dwarfs in the Southern hemisphere is now rapidly growing thanks to the public surveys carried out by the European Southern Observatory (ESO) with the Very Large Telescope (VLT) Survey Telescope (VST; Schipani et al. 2012); ATLAS (Shanks et al. 2015); VPHAS+ (Drew et al. 2014) and KIDS (de Jong et al. 2013). In a pilot study, we have identified white dwarfs at low Galactic latitudes by applying...
we estimate the catalogue to contain candidates with flexible efficiency and completeness, from which

\( \text{VST ATLAS is primarily a cosmology-focused survey aiming to} \)

.. figure:: ATLAS2D.png

Figure 1. Sky distribution of the \( \approx 39\,000 \) white dwarfs confirmed to date. Only \( \approx 15\% \) of them are located below the equator.

### Table 1. Summary of the white dwarf candidate selection in ATLAS.

| Description                                                                 | Value |
|-----------------------------------------------------------------------------|-------|
| ATLAS objects in initial colour cut                                          | 12\,359 |
| Of which with no proper motion                                               | 952   |
| Magnitude limit of final sample                                             | \( g \leq 19 \) |
| Final sample of white dwarf candidates (Section 5)                          | 11\,407 |
| High confidence white dwarf candidates (\( P_{\text{WD}} \geq 0.41 \))       | \( \approx 4200 \) |
| Also in Gentile Fusillo et al. (2015a) catalogue                           |       |
| Of SDSS white dwarf candidates                                              | 879   |
| Of which confirmed white dwarfs                                             | 130   |
| Of which confirmed contaminants                                              | 171   |

traditional colour-cuts to VPHAS+ photometry (Raddi et al. 2016). Here, we present a catalogue of 11\,407 colour-selected sources from ATLAS for which we calculated probabilities of being white dwarfs (\( P_{\text{WD}} \)) according to the method described in Gentile Fusillo et al. (2015a). The \( P_{\text{WD}} \) values allow for selection of ATLAS white dwarf candidates with flexible efficiency and completeness, from which we estimate the catalogue to contain \( \approx 4100 \) genuine white dwarfs (Table 1).

In the following two sections, we briefly summarize the ATLAS survey and describe the properties of the photometric system, and how it compares to SDSS photometry. In Section 4, we briefly outline the methodology used to combine photometry and proper motions to calculate \( P_{\text{WD}} \) values. The catalogue of white dwarf candidates is presented in Section 5. The completeness of the catalogue and the spectroscopic confirmation of some white dwarf candidates are discussed in Section 6. The last section is dedicated to our conclusions.

### 2 VST ATLAS

VST ATLAS is primarily a cosmology-focused survey aiming to image 4700 deg\(^2\) of the Southern Sky at high galactic latitudes \( |b| > 30^\circ \) in five bands (\( ugriz \)) to comparable depths to the SDSS in the north. The ATLAS footprint is divided into two contiguous blocks in the North and South Galactic Caps (NGC, SGC). The ATLAS SGC area lies in the ranges 21\( h^3 30^m < RA < 04^h 00^m \) and \( -40^\circ < \text{Dec.} < -10^\circ \), whilst the NGC area lies in the ranges 10\( h^0 00^m < RA < 15^h 30^m \) and \( -20^\circ < \text{Dec.} < -2.5^\circ \) plus 10\( h^0 00^m < RA < 15^h 00^m \) and \( -30^\circ < \text{Dec.} < -20^\circ \) (Fig. 2).

The survey is carried out at the 2.6-m VST, located at Cerro Paranal in Chile. The telescope mounts at the prime focus a 1 deg\(^2\) wide imaging instrument, the OmegaCAM (Kuijken 2011), which consists of 32 CCDs of 4k \( \times \) 2k pixels each. The narrow gaps between the individual CCDs allow for an overall geometric filling factor of 91.4 per cent (see Shanks et al. 2015, for more details).

The ATLAS band-passes are similar to those of the SDSS filters. Observations are taken in pairs for each filter and exposure times of 60 s for \( u \), 50 s for \( g \) and 45 s for \( r \), \( i \) and \( z \). The imaging data is reduced by the Cambridge Astronomical Survey Unit using the VST data flow software. Images are trimmed and de-biased using nightly calibration frames and then flat-fielded using accumulated monthly stacked twilight sky flats. The frames are then corrected for cross-talk and de-fringed, if necessary. The resulting imaging data comprise the combination of the two individual images for each of the original CCDs (Shanks et al. 2015). For the analysis presented here, we used the latest internal data release available on 2016 April 25. This release includes coverage in all five filters and photometric quality flags for \( \geq 2400 \) deg\(^2\) of the sky, surpassing the publicly available Data Release 3.

### 3 ATLAS VERSUS SDSS

VST ATLAS uses the same optical filters as SDSS (\( ugriz \)) and in many ways aims to be the Southern hemisphere counterpart of SDSS. However, though the filter systems are nominally the same, the actual filter transmission curves have small differences, the detectors are not the same, the observing conditions at the telescope sites are different, and the flux calibration is conducted in different ways. As a result, ATLAS and SDSS magnitudes, and therefore colours, are not perfectly equivalent. As part of their re-calibration of ATLAS photometry to the AB system, Shanks et al. (2015) carried out a detailed comparison of SDSS and ATLAS photometry. ATLAS and SDSS overlap over an equatorial region of \( \approx 300 \) deg\(^2\) covering parts of both the NGC \( (10^h \lesssim RA \lesssim 15^h 30^m; -3.5^\circ \lesssim \text{Dec.} \lesssim -2^\circ ) \) and the SGC \( (22^h 40^m \lesssim RA \lesssim 3^h; -11^\circ \lesssim \text{Dec.} \lesssim -9^\circ ) \). Shanks et al. (2015) used the objects in the NGC overlapping region to develop a set of colour-dependent equations to convert ATLAS (AB) magnitude in equivalent SDSS magnitudes:

\[
\begin{align*}
\mu_{\text{SDSS}} &= \mu_{\text{ATLAS}} + 0.01 \times (u - g) + 0.27, \\
\beta_{\text{SDSS}} &= \beta_{\text{ATLAS}} - 0.05 \times (g - r) - 0.06, \\
\gamma_{\text{SDSS}} &= \gamma_{\text{ATLAS}} + 0.03 \times (g - r) - 0.035, \\
\iota_{\text{SDSS}} &= \iota_{\text{ATLAS}} - 0.025, \\
\zeta_{\text{SDSS}} &= \zeta_{\text{ATLAS}} - 0.04 \times (i - z) + 0.04.
\end{align*}
\]

Since our selection method for white dwarf candidates makes use of a probability map in reduced proper motion–colour space that was initially developed from SDSS data (see Section 5), it is of
paramount importance to have reliable SDSS-equivalent ATLAS magnitudes (ATLAS$_{SDSS}$ from here on). In order to evaluate the robustness of the magnitude transformations developed by Shanks et al. (2015), in particular their applicability to blue objects, we carried out some further comparison with SDSS. We retrieved the available SDSS photometry of all ATLAS sources in the overlapping regions with clean $g \leq 19.5$ SDSS photometry ($\approx 112 000$ objects). We then applied equation (1) to the ATLAS photometry and compared the ATLAS$_{SDSS}$ magnitudes with the SDSS ones (Fig. 3). We find that the mean values of SDSS–ATLAS$_{SDSS}$ magnitudes for the objects in our overlapping samples are: $u = 0.0109 \pm 0.0003$, $g = 0.0089 \pm 0.0001$, $r = 0.0086 \pm 0.0001$, $i = 0.0098 \pm 0.0002$, $z = 0.011 \pm 0.0003$. These mean differences are smaller than the typical uncertainties in the SDSS and ATLAS magnitude. We therefore conclude that ATLAS$_{SDSS}$ magnitudes are, for most intents and purposes, equivalent to SDSS ones, and our selection method for white dwarf candidates (Gentile Fusillo et al. 2015a) can be directly applied to them.

4 COLOUR SELECTION AND PROPER MOTIONS

Using the free form SQL query tool available on the OmegaCAM Science Archive webpage, we retrieved photometry for all ATLAS sources that have been observed in all five filters, marked as ‘stellar’ or ‘probable stellar’ and with no ‘important’ quality issue (Table 2). We then applied the magnitude conversions described by equation (1) to calculate ATLAS$_{SDSS}$ magnitudes for all our sources. The first step in our photometric selection method for white dwarf candidates involves applying a set of colour constraints that broadly select all blue sources (Table 3). These colour-cuts are designed to include all white dwarfs with $T_{\text{eff}} \gtrsim 7000$ K and are required to reduce the initial sample to a more manageable size, but they are not sufficient to eliminate contamination from QSO and other blue objects (i.e. sub-dwarfs, A stars; for more details see Gentile Fusillo et al. 2015a). This initial broad colour selection resulted in a sample of 12 359 blue ATLAS sources. ATLAS does not provide proper-motion measurements, thus we decided to retrieve those from the recently published Absolute Proper motions Outside the Plane (APOP, Qi et al. 2015) catalogue. APOP proper motions are calculated from carefully re-reduced photographic plates from the STScI Catalog of Objects and Measured Parameters from All-Sky Surveys (COMPASS) archive of the GSC-II project (Lasker & STSCI Sky-Survey Team 1998). APOP covers 22 525 deg$^2$ and provides proper motions for 100 774 153 objects to the limiting magnitude of R $\approx 20.8$ with typical uncertainties ranging between 4 and 9 mas yr$^{-1}$. However, the astrometry of APOP and ATLAS corresponds to observations taken several years apart and most white dwarfs have high proper motions, typically ranging from 20 to 200 mas yr$^{-1}$. White dwarfs can therefore move significantly over a few years to decades and a simple cross match between ATLAS and APOP using a fixed matching radius can easily lead to several mis-matches or missing objects.

We therefore divided our cross-matching procedure in three separate steps. For each ATLAS object, we first retrieved every matching APOP source within a radius of 30 arcsec (typically four to eight objects) and compared the modified Julian date (MJD) of the ATLAS observation with that of APOP (by definition at epoch J2000 so MJD 51544). We defined an epoch difference $\Delta t = \text{MJD}_{\text{ATLAS}} - 51544$ and then used the proper motions and J2000 positions from APOP to compute predicted positions at the epoch of the ATLAS imaging for all objects in the first cross-match (Fig. 4). This coordinate ‘forward projection’ is carried out according to

$$
\alpha = \alpha_{\text{APOP}} + \left( \frac{\mu_\alpha}{\cos(\delta_{\text{APOP}})} \right) \times \frac{\Delta t}{365.25},
$$

$$
\delta = \delta_{\text{APOP}} + \mu_\delta \times \frac{\Delta t}{365.25},
$$

where $\mu_\alpha$ and $\mu_\delta$ are the objects proper motions in right ascension and declination, respectively. Finally, we consider a true match to be the closest object whose forward projected coordinates fall within 2 arcsec of the ATLAS ones. In cases where more than one matching object is found within 2 arcsec (a few tens within the entire sample), we select the best match by visually inspecting the magnitudes of the matching pairs and their angular separation.

Following this procedure, we obtained proper motions for 11 407 objects. The most likely explanation for the 952 ATLAS objects for which we could not find a counterpart in APOP is that they could not be reliably matched up on the photographic plates used by APOP.

---

1 as defined on the quality bit flags description at http://osa.roe.ac.uk.
5 WHITE DWARF CANDIDATES SELECTION

In order to identify reliable white dwarf candidates among ATLAS sources, we rely on the photometric selection method presented in Gentile Fusillo et al. (2015a) that can be used to assign a ‘probability of being a white dwarf’ (\(P_{WD}\)) to any object with available multiband photometry and proper motion. In this section, we briefly summarize the details of the selection method; for a full description refer to Gentile Fusillo et al. (2015a). The \(P_{WD}\) values rely on a probability map that traces the distribution of spectroscopically confirmed white dwarfs and contaminant objects selected from SDSS in colour and reduced proper motion space, which we therefore adopted for our selection method. The \(P_{WD}\) values are computed as

\[ P_{WD} = g + 5 \text{ log} \mu + 5, \]

where \(\mu\) is the proper motion in arcsec yr\(^{-1}\). This probability map effectively traces which areas in colour-\(H\) space are more likely populated by either white dwarfs or contaminants. In our work on SDSS photometry, we determined that the strongest discrimination between white dwarfs and contaminants is obtained in the \((g - z, H_g)\) space, which we therefore adopted for our selection method. The final map was constructed using a training sample of over 27 000 objects (different types of white dwarfs, quasars and stellar contaminants) that were classified by visual inspection of their SDSS spectra. By combining the \((g - z, H_g)\) position of a test object with this probability map, we can compute a quantity that directly indicates how likely it is for the object to be a white dwarf, in other words our \(P_{WD}\). We have shown above that ATLAS\(_{SDSS}\) magnitudes are equivalent to the SDSS ones. We therefore calculated \(H_g\) for all ATLAS objects using the ATLAS\(_{SDSS}\) magnitudes and the APOP proper motions, and directly applied the Gentile Fusillo et al. (2015a) selection method to calculate \(P_{WD}\) for all 11 407 ATLAS sources in our sample. In Table 4, we summarize the content of our final catalogue of ATLAS white dwarf candidates.

We also performed a cross-match of our catalogue with the \(Gaia\) DR1 source catalogue (Gaia Collaboration et al. 2016) and provide \(Gaia\) source ID and G-band mean magnitude for all matching sources. \(Gaia\) is able to resolve objects with a sky separation of 0.23 arcsec (de Bruijne et al. 2015), a resolution much higher than what is achievable by VST ground based observations. As a result, we found two ATLAS objects (ATLASJ235435.65–290704.08 and ATLASJ121100.93–057524.23) that were each matched to two \(Gaia\) sources both with an angular separation of <1 arcsec. These objects are likely to be binary systems that were resolved with \(Gaia\), but not in ATLAS. ATLASJ121100.93–057524.23 could be of particular interest being a relatively bright white dwarf candidate (\(P_{WD} = 0.71, g = 15.9\)) with a potential faint close companion (\(G = 18.4\)). Out of the five ATLAS bands, we find that \(r\) is the one closest to \(Gaia\) G particularly for sources with \(g - r \geq 0\) where the mean difference \(G-r\) is 0.12 mag.

6 DISCUSSION

6.1 Comparison with SDSS

In Gentile Fusillo et al. (2015a), we used an independent sample of spectroscopically confirmed white dwarfs and contaminants from SDSS DR9 and DR10 and later LAMOST DR3 (Gentile Fusillo et al. 2015b) to establish the \(P_{WD}\)-based ATLAS white dwarf catalogue.

Table 2. SQL casjob flags used to select ATLAS point sources with reliable photometry from the OmegaCAM Science Archive webpage.

| Constraint | Effect |
|------------|--------|
| (mergedClass = -1) OR (mergedClass = -2) AND (uppErrBits | gppErrBits | rppErrBits | ippErrBits | zppErrBits) < 65536 | selects objects marked as ‘stellar’ or ‘probable stellar’ |
| OR (uppErrBits | gppErrBits | rppErrBits | ippErrBits | zppErrBits) & 0x00400040 != 0 | exclude sources with any ‘important’ quality issues |
| does not exclude ‘source within a dither offset of the stacked frame boundary’ |

Table 3. Equations describing the colour and magnitude constraints used to select sources in the ATLAS footprint. The colour cuts were applied to the ATLAS magnitudes after converting them into SDSS equivalent ones.

| Colour | Constraint | Effect |
|--------|------------|--------|
| \((u - g)\) | \(\leq 3.917 \times (g - r) + 2.344\) | selects objects within \(1\) arcsec of \(Gaia\) G-band magnitude |
| \((u - g)\) | \(\leq 0.098 \times (g - r) + 0.721\) | selects objects within \(2\) arcsec of \(Gaia\) G-band magnitude |
| \((u - g)\) | \(\leq 1.299 \times (g - r) - 0.079\) | selects objects within \(3\) arcsec of \(Gaia\) G-band magnitude |
| \((g - r)\) | \(\leq 0.450\) | selects objects within \(4\) arcsec of \(Gaia\) G-band magnitude |
| \((g - r)\) | \(\leq 2.191 \times (r - i) - 0.638\) | selects objects within \(5\) arcsec of \(Gaia\) G-band magnitude |
| \((r - i)\) | \(\leq -0.452 \times (i - z) + 0.282\) | selects objects within \(6\) arcsec of \(Gaia\) G-band magnitude |
| \(g\) | \(\leq 19\) | selects objects within \(7\) arcsec of \(Gaia\) G-band magnitude |

Figure 4. ATLAS g-band image centred at the position of one of our white dwarf candidates. The blue circle represents the 30 arcsec radius area used for the first cross-match with APOP. 2 arcsec radius circles are shown centred on the J2000 APOP coordinates of all matching sources in the initial cross-match and the red arrows indicate how the objects moved between J2000 and the ATLAS epoch of observation. The white circle indicates the final 2 arcsec matching radius around the ATLAS source.
Table 4. Format of the catalogue of VST ATLAS white dwarfs candidates. The full catalogue can be accessed online via VizieR.

| Column no. | Heading                                      | Description                                                                 |
|-----------|----------------------------------------------|-----------------------------------------------------------------------------|
| 1         | VST ATLAS name                               | ATLAS objects name (ATLAS + J2000 coordinates)                              |
| 2         | ATLAS ID                                     | Unique ID identifying the photometric source in ATLAS                        |
| 3         | ra                                           | Right ascension                                                             |
| 4         | dec                                          | Declination                                                                 |
| 5         | $P_{WD}$                                     | The probability of being a WD computed for this object                       |
| 6         | umag                                         | ATLAS u-band magnitude                                                      |
| 7         | umag err                                     | ATLAS u-band magnitude uncertainty                                          |
| 8         | gmag                                         | ATLAS g-band magnitude                                                      |
| 9         | gmag err                                     | ATLAS g-band magnitude uncertainty                                          |
| 10        | rmag                                         | ATLAS r-band magnitude                                                      |
| 11        | rmag err                                     | ATLAS r-band magnitude uncertainty                                          |
| 12        | imag                                         | ATLAS i-band magnitude                                                      |
| 13        | imag err                                     | ATLAS i-band magnitude uncertainty                                          |
| 14        | zmag                                         | ATLAS z-band magnitude                                                      |
| 15        | zmag err                                     | ATLAS z-band magnitude uncertainty                                          |
| 16        | MJD                                          | Modified julian date of ATLAS observation                                   |
| 17        | pmra                                         | APOP proper motion in right ascension (mas yr$^{-1}$)                        |
| 18        | pmra err                                     | APOP proper motion in right ascension uncertainty (mas yr$^{-1}$)            |
| 19        | pmdec                                        | APOP proper motion in declination (mas yr$^{-1}$)                           |
| 20        | pmdec err                                    | APOP proper motion in declination uncertainty (mas yr$^{-1}$)               |
| 21        | human class                                  | Classification of the object based on inspection of its available spectrum   (section 6.2) |
| 22        | Simbad type1                                 | Currently available primary Simbad classifications                           |
| 23        | Simbad type2                                 | Currently available secondary Simbad classifications                         |
| 24        | Gaia ID                                      |Gaia DR1 source ID                                                          |
| 25        | Gmag                                         |Gaia DR1 G-band mean magnitude                                              |

e et al. 2015b) to demonstrate the efficiency of the selection method and the completeness of our catalogue of SDSS white dwarf candidates. However, similarly large spectroscopic samples do not exist for the Southern hemisphere and therefore we cannot test in the same way the robustness of the selection method when applied to ATLAS photometry. None the less, as a result of the overlap of ATLAS with SDSS, 879 objects appear in both the Gentile Fusillo et al. (2015a) catalogue of SDSS white dwarf candidates and in the ATLAS catalogue presented here. This sample includes 130 white dwarfs and 171 contaminants confirmed by SDSS spectroscopy (as of SDSS DR12 Alam et al. 2015) that enable us to carry out some valuable tests on the ATLAS sample of white dwarf candidates.

Fig. 5 shows that the vast majority of the 130 white dwarfs have $P_{WD}$ (ATLAS) > 0.8 while over 85 per cent of the 171 contaminants have $P_{WD}$ (ATLAS) < 0.2. Though this test is limited to small sample sizes, it is evident that the $P_{WD}$ calculated from ATLAS and APOP data provide a clear discrimination between white dwarfs and contaminants.

Using the same spectroscopic sample, we can also calculate that a confidence cut that includes all ATLAS objects with $P_{WD}$ ≥ 0.41 results in a 96 per cent completeness and 87 per cent efficiency in selecting white dwarfs. These numbers are very similar to those obtained from the catalogue of SDSS white dwarf candidates (Gentile Fusillo et al. 2015a) when applying the same cut in $P_{WD}$. We also compared the surface density of ATLAS and SDSS white dwarf candidates with $P_{WD}$ ≥ 0.41, and for both samples, we find an average of ≃1.8 objects per deg$^2$. These results suggest that our catalogue of ATLAS white dwarf candidates should be as complete and reliable as the SDSS catalogue presented in Gentile Fusillo et al. (2015a).

The common ATLAS and SDSS white dwarf candidates also allow us to directly compare $P_{WD}$ values calculated using ATLAS and APOP with those calculated using SDSS data. We find that the $P_{WD}$ values are largely consistent with an average difference $|P_{WD(\text{ATLAS})} - P_{WD(\text{SDSS})}| = 0.042 ± 0.03$.

However, ≃4 per cent of the objects in the overlapping SDSS and ATLAS sample show significantly inconsistent $P_{WD}$ values, $|P_{WD(\text{ATLAS})} - P_{WD(\text{SDSS})}| ≥ 0.2$. Close inspection of these objects reveals that the cause of such difference in $P_{WD}$ is a marked discrepancy in the SDSS and APOP proper motions, potentially caused by erroneous matching on the original photographic plates used by the surveys. Additionally, despite our best efforts, we cannot fully exclude that a limited number of ATLAS objects may have been matched to the wrong APOP object (see Section 4) leading to a wrong assumed proper motion. Even accounting for this
small number of inconsistencies, we are confident that the $P_{\text{WD}}$ values calculated can be used to reliably select high-confidence dwarf candidates, i.e. Fig. 6 clearly illustrate that the colour–distribution of the ATLAS $P_{\text{WD}} \geq 0.41$ sample is remarkably similar to that of the equivalent sample selected from the Gentile Fusillo et al. (2015a) SDSS catalogue. Taking into account the values of completeness and efficiency calculated before, we estimate that our catalogue contains $\approx 4100$ high-confidence white dwarf candidates.

### 6.2 Spectroscopic follow-up

To further test the reliability of our selection method, we obtained spectra for a total of 185 objects from our catalogue. 169 objects were observed with the two degree field ('2dF') multi-object system of the AAOmega spectrograph on the Anglo Australia Telescope (AAT). These spectra were acquired as part of the 2dF Quasar Dark Energy Survey pilot (Chehade et al. 2016). The observations were made using the 580V and 385R gratings for the blue and red arm of the spectrograph, respectively. This configuration achieves a useful wavelength range between 3700 and 8800 Å. The data reduction was carried out using the 2dFDR\(^2\) data reduction pipeline (for more details see Chehade et al. 2016). Among these 169 targets, we identified 14 new white dwarfs, all of which have $P_{\text{WD}} > 0.7$. The remaining objects are mostly quasars with $P_{\text{WD}} < 0.2$ and only four of them have $P_{\text{WD}} > 0.45$.

We also selected 16 additional targets specifically as high-confidence white dwarf candidates ($P_{\text{WD}} \geq 0.85$) and observed them with the New Technology Telescope (NTT) and the VLT as part of the 2dF Quasar Dark Energy Survey pilot (Chehade et al. 2016). These spectra were acquired as part of the 2dF Quasar Dark Energy Survey pilot (Chehade et al. 2016). The observations were made using the 580V and 385R gratings for the blue and red arm of the spectrograph, respectively. This configuration achieves a useful wavelength range between 3700 and 8800 Å. The data reduction was carried out using the 2dFDR\(^2\) data reduction pipeline (for more details see Chehade et al. 2016). Among these 169 targets, we identified 14 new white dwarfs, all of which have $P_{\text{WD}} > 0.7$. The remaining objects are mostly quasars with $P_{\text{WD}} < 0.2$ and only four of them have $P_{\text{WD}} > 0.45$.

We also selected 16 additional targets specifically as high-confidence white dwarf candidates ($P_{\text{WD}} \geq 0.85$) and observed them with the New Technology Telescope (NTT) and the VLT as part of the 2dF Quasar Dark Energy Survey pilot (Chehade et al. 2016). These spectra were acquired as part of the 2dF Quasar Dark Energy Survey pilot (Chehade et al. 2016). The observations were made using the 580V and 385R gratings for the blue and red arm of the spectrograph, respectively. This configuration achieves a useful wavelength range between 3700 and 8800 Å. The data reduction was carried out using the 2dFDR\(^2\) data reduction pipeline (for more details see Chehade et al. 2016). Among these 169 targets, we identified 14 new white dwarfs, all of which have $P_{\text{WD}} > 0.7$. The remaining objects are mostly quasars with $P_{\text{WD}} < 0.2$ and only four of them have $P_{\text{WD}} > 0.45$.

We also selected 16 additional targets specifically as high-confidence white dwarf candidates ($P_{\text{WD}} \geq 0.85$) and observed them with the New Technology Telescope (NTT) and the VLT as part of the 2dF Quasar Dark Energy Survey pilot (Chehade et al. 2016). These spectra were acquired as part of the 2dF Quasar Dark Energy Survey pilot (Chehade et al. 2016). The observations were made using the 580V and 385R gratings for the blue and red arm of the spectrograph, respectively. This configuration achieves a useful wavelength range between 3700 and 8800 Å. The data reduction was carried out using the 2dFDR\(^2\) data reduction pipeline (for more details see Chehade et al. 2016). Among these 169 targets, we identified 14 new white dwarfs, all of which have $P_{\text{WD}} > 0.7$. The remaining objects are mostly quasars with $P_{\text{WD}} < 0.2$ and only four of them have $P_{\text{WD}} > 0.45$.

We also selected 16 additional targets specifically as high-confidence white dwarf candidates ($P_{\text{WD}} \geq 0.85$) and observed them with the New Technology Telescope (NTT) and the VLT as part of the 2dF Quasar Dark Energy Survey pilot (Chehade et al. 2016). These spectra were acquired as part of the 2dF Quasar Dark Energy Survey pilot (Chehade et al. 2016). The observations were made using the 580V and 385R gratings for the blue and red arm of the spectrograph, respectively. This configuration achieves a useful wavelength range between 3700 and 8800 Å. The data reduction was carried out using the 2dFDR\(^2\) data reduction pipeline (for more details see Chehade et al. 2016). Among these 169 targets, we identified 14 new white dwarfs, all of which have $P_{\text{WD}} > 0.7$. The remaining objects are mostly quasars with $P_{\text{WD}} < 0.2$ and only four of them have $P_{\text{WD}} > 0.45$.

### 6.3 Spectral analysis

Of the 30 new spectroscopically confirmed white dwarfs, 27 stars have hydrogen-dominated atmospheres (DA), one shows strong Ca H&K lines (DZ, Fig. 7), one has a likely carbon-dominated atmosphere (DQ) and another star does not show strong atmospheric features at the signal-to-noise level of the spectrum we obtained. Two DA white dwarfs display also Zeeman splitting of the hydrogen lines due to moderately strong magnetic fields (DAH, e.g. Fig. 7).

In Table 5, we summarize the spectral classification and we report the atmospheric parameters ($T_{\text{eff}}, \log g$) of the DA white dwarfs, which we have measured through comparison with a grid of Koester (2010) model spectra (Fig. 8). The synthetic spectra were computed with the mixing-length prescription of ML2/α = 0.8, and include the Stark broadening profiles by Tremblay & Bergeron (2009). For the spectral analysis, we used-fitS2 (Napiwotzki et al. 2004) that determines the best-fitting model via $\chi^2$ minimization of the Balmer line profiles for observed and synthetic spectra, using a downhill simplex algorithm (e.g. the AMOEBA routine; Press et al. 1992) and a bootstrap method to assess the uncertainties. For cool DA white dwarfs ($T_{\text{eff}} < 15\,000$ K), we applied the Tremblay et al. (2013) 3D corrections of the atmospheric parameters to account for the inaccurate treatment of convention in 1D models.

The spectroscopic parameters are broadly consistent with the photometric estimates one would derive from comparison with the white dwarf cooling sequences (Fig. 6).

### 6.4 New pulsating white dwarfs

As it continues its tour around the ecliptic plane, the extended Kepler mission (K2) has opened the possibility to observe many new white dwarf cooling sequences (Fig. 6).

---

\(^{2}\)http://www.aao.gov.au/science/software/2dfdr

\(^{3}\)PAMELA was written by T. R. Marsh and can be found in the STARLINK distribution Hawaiki and later releases.

\(^{4}\)MOLLY was written by T. R. Marsh and is available from http://www.warwick.ac.uk/go/trmarsh/software.

\(^{5}\)http://www.eso.org/sci/software/reflex/
white dwarfs, especially those that pulsate. We have utilized this catalogue of candidate white dwarfs from ATLAS for target selection of several Guest Observer proposals (for Field 6, 12 and 15 in K2 Campaign 6). One of our candidates, selected solely based on its $P_{\text{WD}}$ and ATLAS $ugr$ colours, was observed to pulsate: ATLASJ134211.62−073540.1 (EPIC 229227292). In fact, this star became the fourth white dwarf to show aperiodic, large-amplitude outbursts in its K2 observations (Bell et al. 2016). Follow-up spectroscopy from the Southern Astrophysical Research (SOAR) telescope confirmed this is a DA white dwarf with atmospheric parameters corresponding to $T_{\text{eff}} = 1170 \pm 150 \text{ K}$, $\log g = 8.10 \pm 0.05$, $M_{\text{WD}} = 0.62 \pm 0.03$. This is now the second-brightest white dwarf known to show such outbursts, which may arise result from a parametric resonant coupling (Hermes et al. 2015).

Additionally, several of the white dwarfs analysed in Table 5 have temperatures and gravities near the empirical DA V instability metric resonant coupling (Hermes et al. 2015).
strip. We followed-up four of these stars with high-speed photometry from the SOAR at Cerro Pachon in Chile. All targets were observed with the Goodman spectrograph in imaging mode using 20 s exposures through an S8612 filter. Three of the observed white dwarfs do not show photometric variability, with good limits on a lack of pulsations. ATLASJ023320.65−320310.88 was observed for 2.0 h and does not vary to a limit of 0.8 ppt (1 ppt = 0.1 per cent). ATLASJ214039.37−341920.25 was observed for 2.4 h and does not vary to a limit of 2.0 ppt. ATLASJ224510.44−383645.71 was observed for 2.1 h and does not vary to a limit of 2.9 ppt. However, we have detected significant variability in a 1.8 h run on ATLAS224653.56−385651.24: a 4.9(3) ppt peak at 1502.0 ± 10.3 s. If confirmed, this would be one of the coolest (and longest-period) pulsating white dwarfs detected to date. Within the uncertainties in $T_{\text{eff}}$ and log g (Table 5), the two pulsating white dwarfs can be placed inside of the empirical ZZ Ceti instability strip and similarly the three stars observed not to vary can be placed outside it.

7 CONCLUSION

We presented the application of our selection method for photometric white dwarfs candidates (Gentile Fusillo et al. 2015a) to the latest internal data release of the VST ATLAS survey combined with proper motions from APOP. The resulting catalogue contains 11 407 ATLAS sources with computed $P_{\text{WD}}$. Using a small number of SDSS spectroscopically confirmed white dwarfs and contaminants, we calculated that a confidence cut at $P_{\text{WD}} \geq 0.41$ produces a sample of white dwarfs that is 96 per cent complete with an efficiency of 87 per cent. We estimate that our catalogue contains $\approx4200$ high-confidence white dwarf candidates the majority of which have not yet received spectroscopic follow-up. Only $\sim$15 per cent of the white dwarfs known to date are located in the Southern hemisphere and our catalogue therefore constitute a significant improvement on the current north–south knowledge gap.

Among these thousands of new white dwarfs, we expect to find several systems of particular interest: metal polluted white dwarfs (most likely more than 1000 in the final ATLAS footprint) that will improve current statistics on planetary debris abundances, a few tens of white dwarfs with detectable debris discs that can be identified combining our catalogue with IR data from the Vista Hemisphere Survey (VHS, McMahon et al. 2013) and WISE (Wright et al. 2010), several magnetic white dwarfs and white dwarfs with rare atmospheric composition (e.g. DQ) like those already identified in our limited spectroscopic follow-up (Section 6.2) and more pulsating white dwarfs (Section 6.4). The application of our catalogue to most white dwarfs population studies will ultimately require spectroscopic follow-up. The possibility to rely on the $P_{\text{WD}}$ allows one to tailor future spectroscopic observations prioritising efficiency (and therefore high $P_{\text{WD}}$ targets) for single target observations or completeness in large scale campaigns.

ACKNOWLEDGEMENTS

We thank the anonymous referee for the fast and constructive comments received. The research leading to these results has received funding from the European Research Council under the European Union’s Seventh Framework Programme (FP/2007-2013)/ERC Grant Agreement n.320964 (WDTracer). Support for this work was provided by NASA through a Hubble Fellowship grant HST-HF2-51357.001-A. This paper is based on observations made with ESO Telescopes at the Paranal Observatory under programme ID 095.D-0406(B), 095.D-0802(B), 097.D-1029(A), 177.A-3011 (A-I) and also based on observations obtained at the Southern Astrophysical Research (SOAR) telescope, which is a joint project of the Ministério da Ciência, Tecnologia, e Inovação da República Federativa do Brasil, the U.S. National Optical Astronomy Observatory, the University of North Carolina at Chapel Hill and Michigan State University. Funding for SDSS-III has been provided by the Alfred P. Sloan Foundation, the Participating Institutions, the National Science Foundation and the U.S. Department of Energy Office of Science. The SDSS-III website is http://www.sdss3.org/. SDSS-III is managed by the Astrophysical Research Consortium for the
 Participating Institutions of the SDSS-III Collaboration including the University of Arizona, the Brazilian Participation Group, Brookhaven National Laboratory, Carnegie Mellon University, University of Florida, the French Participation Group, the German Participation Group, Harvard University, the Instituto de Astrofísica de Canarias, the Michigan State/Notre Dame/JINA Participation Group, Johns Hopkins University, Lawrence Berkeley National Laboratory, Max Planck Institute for Astrophysics, Max Planck Institute for Extraterrestrial Physics, New Mexico State University, New York University, Ohio State University, Pennsylvania State University, University of Portsmouth, Princeton University, the Spanish Participation Group, University of Tokyo, University of Utah, Vanderbilt University, University of Virginia, University of Washington and Yale University.

**REFERENCES**

Alam S. et al., 2015, ApJ, 219, 12
Bell K. J. et al., 2016, ApJ, 829, 82
Bergeron P., Saffer R. A., Liebert J., 1998, ApJS, 161, 394
Browne W. R., Kilic M., Allende Prieto C., Kenyon S. J., 2010, ApJ, 723, 1072
Castanheira B. G. et al., 2004, A&A, 413, 623
Catalán S., Isen J., García-Berro E., Ribas I., 2008, MNRAS, 387, 1693
Chehade B. et al., 2016, MNRAS, 459, 1179
de Bruijne J. H. J., Allen M., Azaz S., Krone-Martins A., 2006, A&A, 394, 957
Dufour P., Euchner F., Jordan S., 2002, A&A, 394, 957
Dufour P. et al., 2007, ApJ, 663, 1291
Dufour P., Kilic M., Fontaine G., Bergeron P., 2012, ApJ, 719, 803
Eisenstein D. J. et al., 2006, ApJS, 167, 40
Falcon R. E., Winget D. E., Montgomery M. H., Williams K. A., 2010, ApJ, 712, 585
Farihi J., Becklin E. E., Zuckerman B., 2005, ApJS, 161, 394
Farihi J., Jura M., Zuckerman B., 2009, ApJ, 694, 805
Gaia Collaboration et al., 2016, A&A, 595, A2
Gänsicke B. T., Euchner F., Jordan S., 2002, A&A, 394, 957
Gänsicke B. T., Marsh T. R., Southworth J., Rebassa-Mansergas A., 2006, Science, 314, 1908
Gänsicke B. T., Koester D., Girven J., Marsh T. R., Southworth J., 2010, Science, 327, 188
Gentile Fusillo N. P. et al., 2015b, MNRAS, 452, 765
Gentile Fusillo N. P., Gänsicke B. T., Greiss S., 2015a, MNRAS, 448, 2260
Gentile Fusillo N. P., Hermsen E. J., Gänsicke B. T., 2016, MNRAS, 455, 2295
Giammicheli N., Bergeron P., Dufour P., 2012, ApJ, 199, 29
Girven J., Gänsicke B. T., Steeghs D., Koester D., 2011, MNRAS, 417, 1210
Greiss S., Gänsicke B. T., Hermes J. J., Steeghs D., Koester D., Ramsay G., Barclay T., Townsley D. M., 2014, MNRAS, 438, 3086
Harris H. C. et al., 2003, AJ, 126, 1023
Hermes J. J. et al., 2014, ApJ, 792, 39
Hermes J. J. et al., 2015, ApJ, 810, L5
Holberg J. B., Bergeron P., 2006, AJ, 132, 1221
Holberg J. B., Oswalt T. D., Sion E. M., 2002, ApJ, 571, 512
Holberg J. B., Sion E. M., Oswalt T., McCook G. P., Foran S., Subasavage J. P., 2008, AJ, 135, 1225
Hollands M. A., Gänsicke B. T., Koester D., 2015, MNRAS, 450, 681
Iben I. J., Ritossa C., García-Berro E., 1997, ApJ, 489, 772
Kepler S. O. et al., 2013, MNRAS, 429, 2934
Kepler S. O. et al., 2015, MNRAS, 446, 4078
Kepler S. O. et al., 2016, MNRAS, 455, 3413
Kepler S. O., Koester D., Ouriq G., 2016, Science, 352, 67
Kleinman S. J. et al., 2013, ApJS, 204, 5
Koester D., 2010, Mem. Soc. Astron. Ital., 81, 921
Koester D., Gänsicke B. T., Farihi J., 2014, A&A, 566, A34
Kuijken K., 2011, The Messenger, 146, 8
Külebi B., Jordan S., Euchner F., Gänsicke B. T., Hirsch H., 2009, A&A, 506, 1341
Lasker B. M., STSCI Sky-Survey Team, 1998, BAAS, 30, 912
Liebert J., Bergeron P., Holberg J. B., 2005, ApJS, 156, 47
Manser C. J. et al., 2016, MNRAS, 455, 4467
Marsh T. R., 1989, PASP, 101, 1032
Marsh T. R., Nelemans G., Steeghs D., 2004, MNRAS, 350, 113
McMahon R. G., Banerji M., Gonzalez E., Kopenov S. E., Bejar V. J., Lodieu N., Rebolo R., VHS Collaboration, 2013, The Messenger, 154, 35
Niapiwotzki R. et al., 2004, in Hilditch R. W., Hensberge H., Pavlovski K., eds., ASP Conf. Ser. Vol. 318, Spectroscopically and Spatially Resolving the Components of the Close Binary Stars, Astron. Soc. Pac., San Francisco, p. 402
Parsons S. G., Marsh T. R., Gänsicke B. T., Drake A. J., Koester D., 2011, ApJ, 735, L30
Press W. H., Teukolsky S. A., Vetterling W. T., Flannery B. P., 1992, Numerical recipes in FORTRAN, The Art of Scientific Computing, Cambridge Univ. Press, Cambridge
Qi Z. et al., 2015, AJ, 150, 137
Raddi R., Gänsicke B. T., Koester D., Farihi J., Hermes J. J., Scaringi S., Breedt E., Girven J., 2015, MNRAS, 450, 2083
Raddi R. et al., 2016, MNRAS, 457, 1988
Rebassa-Mansergas A. et al., 2015, MNRAS, 450, 743
Schipani P. et al., 2012, in Stepp L. M., Gilmorrii Z., Hall J. H., eds., Proc. SPIE Conf. Ser. Vol. 8444, Ground-based and Airborne Telescopes IV, SPIE, Bellingham, p. 84441C
Schmidt G. D., Liebert J., Harris H. C., Dahn C. C., Leggett S. K., 1999, ApJ, 512, 916
Schmidt G. D. et al., 2003, ApJ, 595, 1101
Shanks T. et al., 2015, MNRAS, 451, 4238
Sion E. M., Leckenby H. J., Szkody P., 1990, ApJ, 364, L41
Sion E. M., Holberg J. B., Oswalt T. D., McCook G. P., Wasatonic R., Myszk J., 2014, AJ, 147, 129
Steele P. R. et al., 2013, MNRAS, 429, 3492
Torres S., García-Berro E., Isen J., Figueras F., 2005, MNRAS, 360, 1381
Tremblay P.-E., Bergeron P., 2009, ApJ, 696, 1755
Tremblay P.-E., Ludwig H.-G., Steffen M., Freytag B., 2013, A&A, 552, A13
Tremblay P.-E., Kalirai J. S., Soderblom D. R., Cignoni M., Cummings J., 2014, ApJ, 791, 92
Tremblay P.-E., Cummings J., Kalirai J. S., Gänsicke B. T., Gentile-Fusillo N., Raddi R., 2016, MNRAS, 461, 2100
Vennes S., Kawka A., 2008, MNRAS, 389, 1367
Wilson D. J., Gänsicke B. T., Koester D., Breedt E., Southworth J., Parsons S. G., 2014, MNRAS, 445, 1878
Wright E. L. et al., 2010, AJ, 140, 1868
York D. G. et al., 2000, AJ, 120, 1579
Zuckerman B., Reid I. N., 1998, ApJ, 505, L143

**SUPPORTING INFORMATION**

Supplementary data are available at MNRAS online.

**Table 4.** Format of the catalogue of VST ATLAS white dwarfs candidates. The full catalogue can be accessed online via VizieR.

Please note: Oxford University Press is not responsible for the content or functionality of any supporting materials supplied by the authors. Any queries (other than missing material) should be directed to the corresponding author for the article.

This paper has been typeset from a TeX/LaTeX file prepared by the author.