Search for the coolest white dwarfs in the Galaxy

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Abstract. A number of so-called ultra-cool white dwarfs have been detected in different surveys so far. However, based on anecdotal evidence it is believed that most or all of these ultra-cool white dwarfs are low-mass products of binary evolution and thus not representative for the oldest white dwarfs. Their low mass causes relatively high luminosity making them the first cool white dwarfs detected in relatively shallow surveys. Deeper observations are needed for the oldest, high mass white dwarfs with the longest cooling times. We report results of an ongoing project that combines deep IR and optical data. This combination plus proper motion information will allow an unambiguous identification of very cool white dwarfs, since the spectral energy distributions are very different from other types of stellar objects. The atmospheric parameters that can be derived from the spectral energy distributions together with the proper motions inferred from the IR data can be used to construct the white dwarf luminosity functions for the thick disc and halo populations. From these we will be able to test the early star formation history and initial mass function of the first stellar populations.

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INTRODUCTION

Observations of high-redshift galaxies provide a direct, if blurred, view of the earliest phase of star formation in the Universe, with the initial starbursts having a big impact on further galaxy evolution. Only limited information is available from unresolved populations because observed spectral energy distributions (SEDs) are completely dominated by stars in a narrow mass interval close to the turn-off. Hence, measuring star formation rates requires the adoption of an initial mass function (IMF), with some authors favouring top-heavy prescriptions (e.g. [1]). A direct test is possible locally in our galaxy by studying thick disc and halo stars, which were formed at the same age as the starbursts observed in high-redshift galaxies.

Although all pop. II stars more massive than the Sun evolved away from the main sequence long ago, the early IMF can be reconstructed from the luminosity function (LF) of the relic white dwarf (WD) population. A thin disc WD LF has been measured based on SDSS [2]. Thin disc LFs are a convolution of the IMF, star formation history, initial-final-mass relation... and are almost impossible to invert. The formation history of the halo and thick disc are probably complex, but observations of field stars and globular clusters indicate that most stars are very old formed over a short period of time. So, the interpretation of the thick disc/halo LF is much more straightforward.

Ref. [3] reported a very large population of WDs belonging to the galactic halo –

TABLE 1. Total number of WDs expected in the four WTS fields.

IMF	$N(M_{\rm prog}) > 1.5M_{\odot}$	$N(M_{\rm prog}) > 2.0M_{\odot}$	$N(M_{\rm prog}) > 4.0M_{\odot}$
Salpeter	27	11	1
Baugh	135	94	26
Kennicutt	49	26	2

in line with a top heavy IMF. This result was disputed by [4] and [5], but all these investigations are based on very local samples and large uncertainties remain, because of small number statistics. A particular problem is the lack of confirmed very cool pop. II WDs, which are most interesting, because they evolved from the most massive progenitor stars. Even the pop. I WD LF constructed by [2], comprising of 6,000 WDs selected from the Sloan Digital Sky Survey (SDSS) contains only 35 cool WDs with absolute magnitudes > 15 mag, thus, deeper observations are needed to increase this number.

We participate in a project that is performing a search of thick disc and halo WDs in a very deep infrared survey (WTS) carried out in the *zyJHK* filters with the UKIRT telescope – co-PI'ed by D. Pinfield. The main aim of this survey is the detection of planetary companions to low-mass stars from the transit light curves. WTS will take over the time span of five years many repeat observations in NIR bands with a total coverage of 6 sq. deg. (4 fields). The J band data will be the deepest with a total of 25 hours spent on each field, reaching at least $J = 25$ mag (5σ) by co-adding observations. The *zyHK* data have a depth of 19–21, so these are useful for bright objects. Our proper motion (ppm, μ) work using stacked WTS observations from different epochs indicates a final ppm accuracy of $\approx 1-2$ mas/yr. 50% of the WTS observations are completed and reduced so far. Observations of the four fields are expected to be completed by 2012. We have recently obtained optical data ($g'r'i'$ bands) of one of the WTS fields with the CAHA 3.5m telescope and the LAICA detector. We have granted time to observe the rest of the fields.

SIMULATIONS

Ref. [6] constructed a model of the Galactic WD population, based on the model of Galactic structure by [7]. These simulations consider the WD cooling sequences from [8], the stellar tracks of [9] (Padova Group) to account for the WD progenitor lifetime and the initial-final mass relationship of [10]. The Salpeter IMF is assumed, although the simulations can be run with other IMFs ([1], [11]). The population identification is then based on the results of the kinematic study of [5], calibrated with the local sample [12] and checked against the proper motion selected sample of cool WDs by [3]. According to these simulations more than 1,500 WDs with ppm > 10 mas/yr will be detected in the WTS fields. This model assumes a standard IMF, but numbers could be much higher for a top heavy IMF. Moreover, this sample will contain $\approx$100 cool WDs with $M_V > 15$ mag ($T_{\rm eff}$ <5,000 K), most of them thick disc and halo members, with M_V fainter than the drop-off in the thin disc LF. In Fig. 1 we show these simulations for the thin disc and

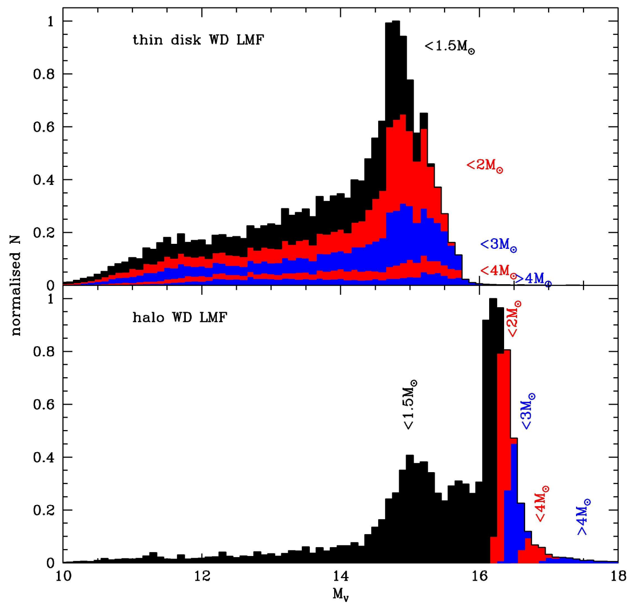

FIGURE 1. Simulated luminosity function of thin disc and halo WD population for a volume limited sample. The progenitor masses are colour coded for the intervals $M_{\rm prog}<1.5M_\odot$, $1.5M_\odot<M_{\rm prog}<2M_\odot$, $2M_\odot<M_{\rm prog}<3M_\odot$, $3M_\odot<M_{\rm prog}<4M_\odot$, $4M_\odot<M_{\rm prog}$. The halo WD luminosity function shows a huge pile-up in the coolest bins. These are WDs produced from higher mass progenitors within a few 10^8 years after the first star formation bursts.

halo WD populations and for different ranges of progenitor masses. As expected, the halo WD LF shows a huge pile-up in the coolest bins corresponding to WDs produced from higher mass progenitors within a few 10^8 years after the first star formation bursts. The situation is different for the thin disk LF, because of the continuous, still ongoing star formation. In Table 1 we show the number of WDs with progenitor masses $M_{\rm prog}$ above threshold masses expected in the four WTS fields. As expected, the predicted number of WDs with massive progenitors is much higher if the Baugh et al. IMF is adopted. With observations for the four WTS fields we will be in a position of ruling out or confirm IMFs predicting an overproduction of high mass stars down to the Kennicutt prescription.

We also checked with the simulated Galactic WD population that ppm criteria allow a good distinction between thin disc WDs on the one hand and thick disc and halo WDs on the other hand, which will allow us to define a clean, but still well sized sample of WDs from the earliest Galactic populations. Distinction between halo and thick disc members will not be as clear cut, but the main aim of this project – reconstruction of the early Universe IMF – will nevertheless be straightforward, because it can be based on the relative numbers of WDs in absolute magnitude (or $T_{\rm eff}$) bins.

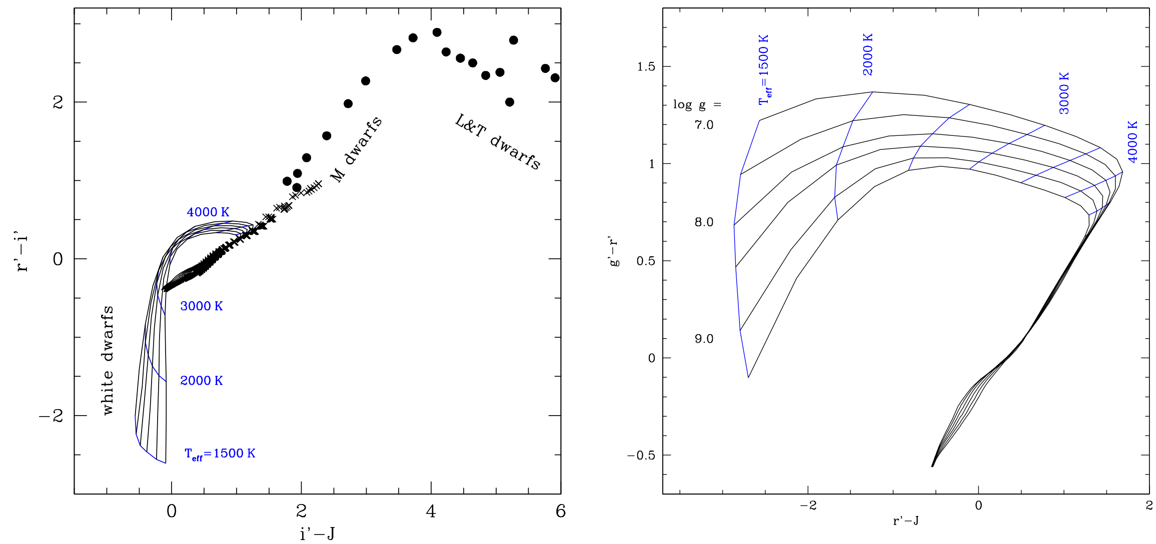

FIGURE 2. *Left:* Colour–colour diagram for different cool objects. Filled circles are empirical colours of M dwarfs and brown dwarfs from [13]. Crosses represent synthetic photometry from [14]. The grid on the left corresponds to synthetic colours for WDs [15] for different temperatures and gravities. *Right:* Another colour–colour diagram that can be used to identify WDs showing good sensitivity in the cool domain.

CHARACTERIZATION OF WHITE DWARF CANDIDATES

A number of so-called ultra-cool WDs that show flux depression in the IR due to hydrogen molecule absorption have been detected so far [16]. However, it is believed that most or all of these ultra-cool WDs are low-mass products of binary evolution and thus not representative for the oldest WDs. Their low mass causes relatively high luminosity making them the first cool WDs detected in relatively shallow surveys. Deeper observations are needed for the oldest, high mass WDs with the longest cooling times. There are some available surveys, e.g. SDSS, that cover a larger area of the sky, but they are too shallow to detect these interesting objects. The combination of very deep IR observations with optical data will allow an unambiguous identification of cool WDs without further follow-up observations, since their spectral energy distributions are very different from other types of cool objects. In Fig. 2 (left) we show a colour–colour diagram for different cool objects. As it can be seen WDs can be easily discerned from other cool objects, and most importantly, the temperature and gravities of cool WDs can be obtained since it shows good sensitivity up to 4,000 K, which is the domain in which we are mainly interested. In Fig. 2 (right) we show another colour–colour digaram showing good $T_{\rm eff}$ / $\log g$ sensitivity for the same domain. Hotter WDs are also needed to normalise the WD LF relative to lower mass progenitors. This can be achieved using a reduced proper motion diagram or other statistical tools [17] even without direct measurements of $\log g$.

From the combination of optical + IR photometry and the ppms (μ) we have been able to identify thick disc/halo WD candidates. In Fig. 3 (left) we show the reduced proper

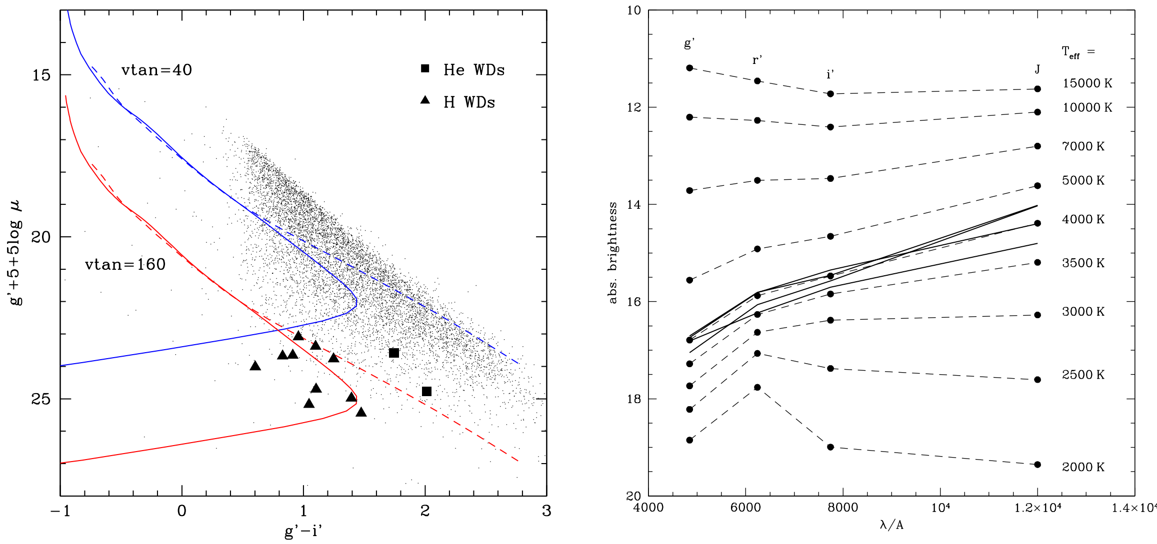

FIGURE 3. *Left:* Reduced proper motion diagram for the data obtained in the last observing run (May 2010). Triangles and squares correspond to our 12 high-ppm WD candidates. The solid lines correspond to the theoretical tracks for H composition for $v_{tan} = 40$ km/s (top) and 160 km/s (bottom). The dashed lines correspond to He composition. Note that some of our WD candidates could have mixed compositions too. *Right:* Theoretical SEDs of WDs for different $T_{\rm eff}$ and $\log g = 8.0$. Solid lines correspond to some of our candidates.

motion ($H_g = g' + 5 + 5\log\mu$) diagram that we obtained using our recent data. We have identified 12 candidates that meet the WD red. ppm criteria $H_g > 15.136 + 2.727(g' - i')$ and have high ppm ($\mu > 0.15$ arcsec/yr), indicating that they belong to the thick disc-halo populations. The triangles and squares correspond to Hydrogen and Helium WD candidates, respectively. The SEDs of WDs are very different from all faint objects showing significant ppm. In Fig. 3 (right) we show the SED of WDs for different $T_{\rm eff}$ [15]. The 2,000-3,000 K models show the characteristic IR flux depression caused by hydrogen (pseudo)-molecules. The solid lines correspond to the magnitudes obtained for the coolest candidates and as it can be seen they match with the WD theoretical models. We have obtained preliminary $T_{\rm eff}$ and $\log g$ determinations for these 12 candidates from a fit to synthetic photometry, confirming that they are cool and have high $\log g$, consistent with single stellar evolution. From the atmospheric parameters, the WD masses can be derived using appropriate cooling sequences (e.g. [18],[19]) and from these the progenitor masses by considering a initial-final mass relationship (e.g. [10],[20]).

CONCLUSIONS AND FUTURE WORK

Thanks to the cool WDs detected in this project we will be able to reconstruct the early Universe IMF from a comparison of the LFs with the WD population simulations of [6] until a self-consistent model is achieved. Some uncertainty is caused by the very poorly known initial-final mass relationship (IFMR) of pop. II WDs, but even a modest variation of the IFMR will not have much impact on our project since our primary indicator of mass will be the WD temperature, and for the halo/thick disc LFs these are mainly determined by the progenitor lifetime, which is well known from stellar evolution models. However, 1) we will use the mass determinations of WDs in our sample to refine the IFMR, and 2) the resulting uncertainties are small compared to the effects claimed by [1].

In the near future our main objective will be to complete the optical imaging of the four WTS fields, then we will be in a position of ruling out or confirm IMFs predicting an overproduction of high mass stars down to the Kennicutt prescription. We will perform a spectroscopic follow-up of the coolest WD candidates to confirm their classification and study the atmospheric properties. The identification and characterization of cool WDs in this project will have an impact on other fields of astrophysics: Hydrogen opacities are rather uncertain at low temperatures. Theoretical work is going on for further improvement (e.g. [21]) but observational benchmarks are important. Note hydrogen have an impact on the IR flux of brown dwarfs as well, which are observed down to much lower temperatures than WDs [22]. We will obtain accurate observational SEDs of cool WDs that will give an unprecedented input to test the theoretical models.

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