

# An ultra-cool white dwarf serendipitously found with COMBO-17

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## ABSTRACT

We report the discovery of an ultra-cool white dwarf in the COMBO-17 survey. So far, only seven objects have been discovered in this rare category of white dwarfs, which are characterized by strong flux depression in the far-red and near-infrared part of the spectrum, presumably due to collisionally induced absorption (CIA). The new object COMBO-17 J114356.08-0144032 has very similar colours to LHS 3250, which was the first of its kind to be recognized. However, at  $R = 21.5$  it is the faintest and possibly most distant such object discovered to date. It is the only such object in COMBO-17 at  $R < 23$ ; due to the small sky coverage of  $0.78 \square^\circ$  this chance discovery can not provide any constraints on the abundance of faint ultra-cool white dwarfs. We speculate on the basis of the proper motion that this new object is probably a member of the Galactic (thin) disk.

**Key words.** stars: individual: COMBO-17 J1143 – white dwarfs

## 1. Introduction

Cool white dwarfs in the disk of the Milky Way can reveal its age and give clues about its early star formation history. Most of the uncertainty in the age is propagated from the cooling tracks of white dwarfs and not so much given by observational samples of cool white dwarfs. However, it came as a surprise that white dwarfs below 5000 K surface temperature do not show redder colours with lower temperature. Instead, collisionally induced absorption (CIA) by hydrogen molecules suppresses the near-infrared spectrum (Bergeron et al. 1994).

Recently, a new terminology has differentiated between *cool* and *ultra-cool* white dwarfs, which have temperatures above and below 4000 K, respectively. In ultra-cool white dwarfs CIA is so strong that besides the near-infrared also optical colours are affected, and the white dwarf colour tracks in optical colour diagrams are reverted. The stronger CIA pushes the peak of the spectrum further to the blue with decreasing temperature.

LHS 3250 was the first ultra-cool white dwarf recognized as such after its parallax and hence luminosity were measured (Harris et al. 1999). Six more objects have been found since, using SDSS *gri* colours (Harris et al. 2001, 2004) or large proper motion (Oppenheimer et al. 2001). Currently outstanding questions are the accurate physical description of these objects and their membership to the various Galactic components, i.e. thin disk, thick disk and halo. Presently, the favoured scenario assumes these objects to be old, cool white dwarfs with helium cores and very low masses of  $\sim 1/4 M_\odot$  (Bergeron & Leggett 2002). Modeling the spectra is still a

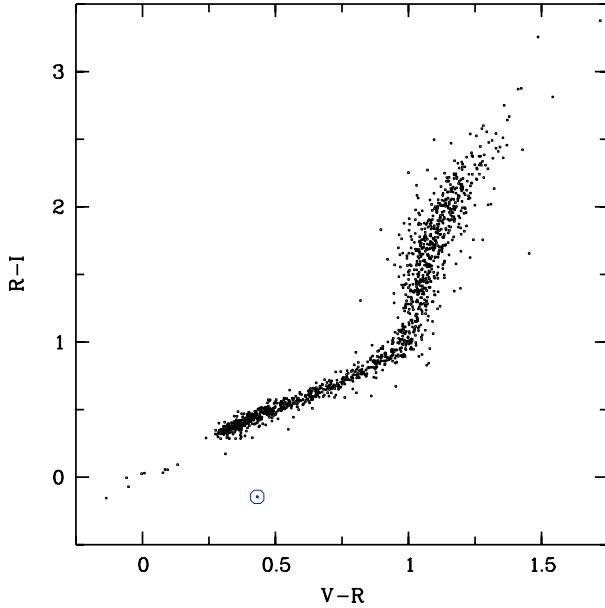
challenge, but  $\sim 3000$  K helium atmospheres with a  $10^{-5}$  contribution from hydrogen seem to be the most promising route.

This letter reports the serendipitous discovery of an ultra-cool white dwarf in the COMBO-17 survey. COMBO-17 is a deep extragalactic multi-band survey characterized by a range of medium-band filters facilitating *fuzzy spectroscopy*. The spectral resolution of the filters is sufficient to differentiate between regular stars, white dwarfs, galaxies and QSOs at  $R \lesssim 23$  and to obtain very accurate photometric redshifts. The new object is currently the faintest, and potentially most distant, known member of its class. All COMBO-17 photometry is reported as Vega-normalised magnitudes, while SDSS colours are given in the AB system.

## 2. Data

### 2.1. COMBO-17 photometry and selection

An unusual object was serendipitously discovered during an inspection of colour-colour diagrams of the S11 field in COMBO-17. The respective diagram showed a sample of objects at  $R = [16, 23]$  which were classified by their SED as stars or white dwarfs (see Wolf et al. 2004 for a discussion of the SED classification in COMBO-17). One object, COMBO-17 J114356.08-0144032 (hereafter COMBO-17 J1143), was noted in a location clearly inconsistent with the stellar colours (see Fig. 1). It is isolated on the sky and not affected by bright neighbors. It shows no signs of magnitude variability above 5% on time scales from weeks to a few years and it is morphologically unresolved.



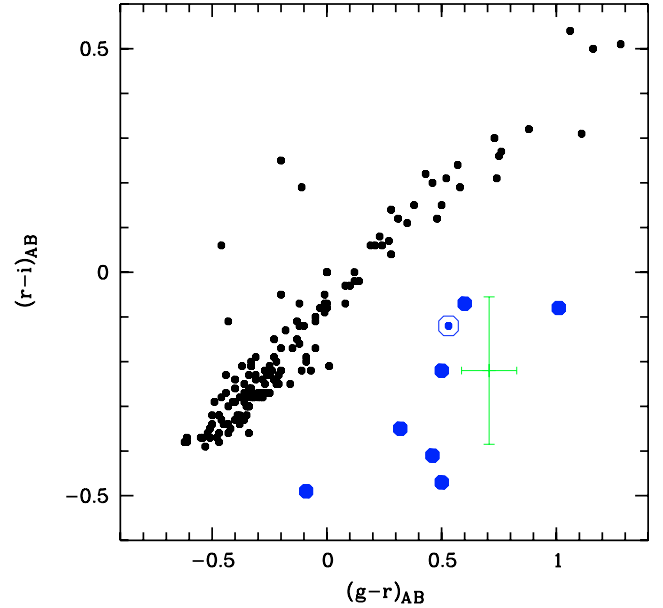
**Fig. 1.** Colour-colour-diagram of COMBO-17-classified stars: 1332 stars and 9 white dwarfs with  $T > 10\,000$  K have been classified in the S11 field in the range of  $R = [16, 23]$ . The object COMBO-17 J1143 marked here by a circle displays large template fitting residuals that are also reflected by its offset from the stellar locus.

Evidently, all stars in the stellar template library are inconsistent with its SED, even when considering composite spectra of binaries. Also, all galaxy and AGN templates are even less consistent with the SED. Hence, we have to suspect that this object is of a more unusual kind.

We searched the three COMBO-17 fields for objects with similar colours, but at  $R < 23$  we only find objects which are clearly QSOs. Fainter than  $R = 23$  our photometry is too noisy to select such objects and differentiate them from QSOs. Hence, our survey contains exactly one object of this kind in an area of  $0.78 \square^\circ$  at  $R < 23$ .

With  $R \sim 21.5$  the object is two magnitudes fainter than the faintest other known ultra-cool white dwarf SDSS J1001. It is well detected in all 17 passbands (see Table 1). A  $J$ -band upper limit is available from the *COMBO-17+4* observations that extend these SEDs into the near-infrared domain (PI Meisenheimer). A  $3\sigma$  upper limit of  $J < 21.6$  is obtained from aperture photometry on the known position of the object. Formally, the object is measured with  $J = 22.8$  and a signal-to-noise ratio around 1.

We have also found the object in the SDSS database, where it is listed as a faint QSO candidate due to its location in the *gri* colour diagram. From SDSS data alone it could not have been identified as an ultra-cool white dwarf candidate, because the  $z$  band is too noisy to differentiate it against QSOs, which are vastly more common at this magnitude. The SDSS colour indices (corrected for negligible interstellar reddening) are  $g - r = 0.71 \pm 0.12$  and  $r - i = -0.23 \pm 0.17$ . The deeper data from COMBO-17 allow to estimate more accurate SDSS colours by comparing the synthetic COMBO-17 colours of the seven known objects as calculated from their spectra. Thus, we find  $g - r = 0.53 \pm 0.05$  and  $r - i = -0.12 \pm 0.05$ .



**Fig. 2.** Colour-colour-diagram of white dwarfs: large symbols show all known ultra-cool white dwarfs, where COMBO-17 J1143 is marked by a circle. Its original SDSS photometry is shown as the data point with error bars. Normal white dwarfs are shown as small symbols (sample by Kleinman et al. 2004). Objects which are redder than normal white dwarfs in  $r - i$  have M dwarf companions while bluer ones show CIA in optical bands.

**Table 1.** Astrometry of the white dwarf COMBO-17 J1143.

$\alpha$ (J2000) run E	$11^{\text{h}}43^{\text{m}}56^{\text{s}}.08$
$\delta$ (J2000) run E	$-01^{\circ}44'03''.21$
$l_{\text{gal}}$	$270^{\circ}.944$
$b_{\text{gal}}$	$56^{\circ}.6172$
$\Delta\alpha_{G-A}$	$-0''.110 \pm 0''.025$
$\Delta\delta_{G-A}$	$-0''.039 \pm 0''.028$
$\Delta\alpha_{H-E}$	$-0''.105 \pm 0''.016$
$\Delta\delta_{H-E}$	$-0''.026 \pm 0''.018$
$\Delta\alpha_{\text{tot}} \text{ yr}^{-1}$	$-0''.050 \pm 0''.006$
$\Delta\delta_{\text{tot}} \text{ yr}^{-1}$	$-0''.014 \pm 0''.007$
Julian epoch $B$ -band run A	1999.122
Julian epoch $R$ -band run E	2000.112
Julian epoch $B$ -band run G	2001.063
Julian epoch $R$ -band run H	2002.332
$v_{\text{tan}}$	$29 \text{ km s}^{-1}$
$v_{\text{rad}}$	unknown
$U_{\text{LSR}}$	$(-10.8-0.009 v_{\text{rad}}) \text{ km s}^{-1}$
$V_{\text{LSR}}$	$(-11.8-0.550 v_{\text{rad}}) \text{ km s}^{-1}$
$W_{\text{LSR}}$	$(-3.8+0.835 v_{\text{rad}}) \text{ km s}^{-1}$

## 2.2. Astrometry and proper motion

Our observations of the S11 field include four imaging epochs from February 1999 to May 2002, which we can compare astrometrically to search for proper motion. The COMBO-17 data reduction has been optimized for photometry but not for accurate astrometry, and general astrometry has internal errors of  $\sim 0.15''$  in every epoch. We achieved the best local astrometric

accuracy by using only reference objects within  $2'$  of the target object, while including also galaxies to provide the reference system. Some stars have been excluded from the astrometric fit because of their own proper motion. We only compare images taken through identical filters to avoid colour-dependent displacement of individual objects as a result of differential refraction. This leaves us with  $B$ -band imaging in February 1999 and January 2001 (PSF on co-added frame  $1''.1$ ) as well as  $R$ -band imaging in January 2000 and May 2002 (PSF  $0''.8$ ).

The positional scatter among 35 galaxies suggests an rms error in the measured position difference of  $0''.026$  and  $0''.017$  in the  $B$ -band and  $R$ -band comparisons, separated by 1.94 yr and 2.21 yr, respectively. The  $R$ -band comparison could be biased by parallax if the object was closer than 50 pc. We measure strong proper motion signals of  $0''.046 \text{ yr}^{-1}$  for a nearby M3 dwarf with  $R = 19$  and of  $\sim 0''.052 \text{ yr}^{-1}$  for the white dwarf COMBO-17 J1143, each with an error of  $\sim 0''.010 \text{ yr}^{-1}$ . The M dwarf is moving in an almost opposite direction, and there is no proper motion companion to the white dwarf among the reference objects.

### 3. Discussion

#### 3.1. Disk or halo object?

Assuming an uncertain luminosity of  $M_V = 16.5 \pm 1.0$  for objects of this kind and colour (following Salim et al. 2004) places COMBO-17-J1143 at a distance of 118 pc with 0.2 dex error ( $^{+70}_{-45}$  pc). This translates into a tangential velocity of  $v_{\text{tan}} = 29 \text{ km s}^{-1}$  relative to the Sun.  $UVW$  velocities after transformation into the local standard of rest (LSR), which is given as  $(U, V, W)_{\odot} = (10.0, 5.2, 7.2) \text{ km s}^{-1}$  by Binney & Merrifield (1998), are listed in Table 1, whereby the radial velocity remains unknown. We compare these numbers with the velocity ellipsoids from Binney & Merrifield (1998) for the Galactic components:

Thin disk:

$$(\sigma_U, \sigma_V, \sigma_W) = (34, 21, 18) \text{ km s}^{-1}, \langle V \rangle = -6 \text{ km s}^{-1}.$$

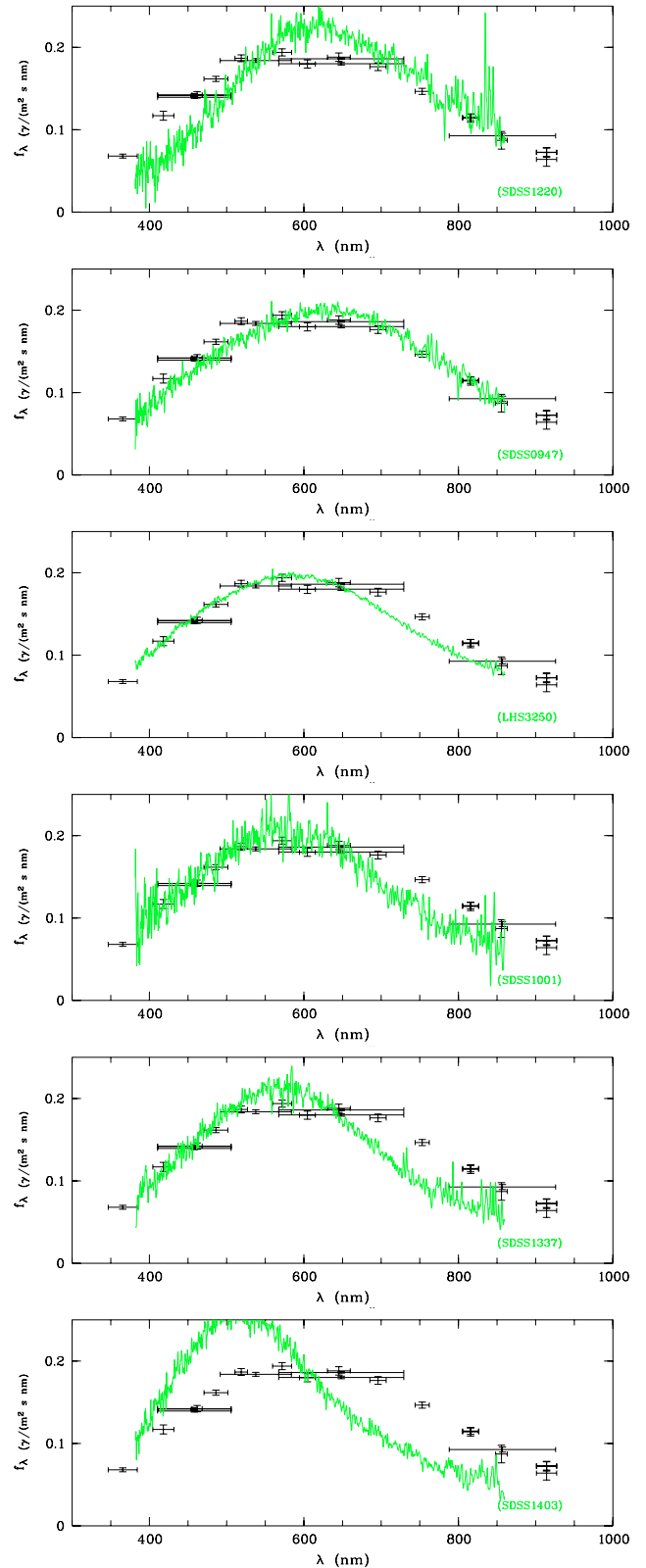
Thick disk:

$$(\sigma_U, \sigma_V, \sigma_W) = (61, 58, 39) \text{ km s}^{-1}, \langle V \rangle = -36 \text{ km s}^{-1}.$$

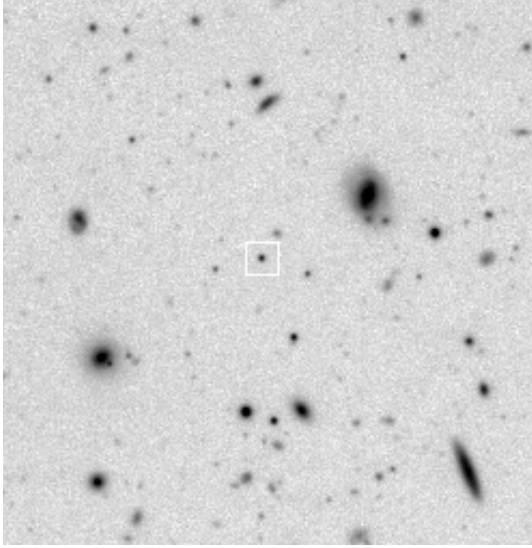
Halo:

$$(\sigma_U, \sigma_V, \sigma_W) = (135, 105, 90) \text{ km s}^{-1}, \langle V \rangle = -185 \text{ km s}^{-1}.$$

Hence, we determine the likelihood ratio for membership to these three components based only on the proper motion and the ellipsoids but not considering the errors on the proper motion, whereby we marginalise over the unknown radial velocity within  $v_{\text{rad}} = [-300, 300] \text{ km s}^{-1}$ . We get  $(p_{\text{thin}}, p_{\text{thick}}, p_{\text{halo}}) = (0.82, 0.16, 0.02)$ . Membership of the thin disk appears to be four times more likely than of the thick disk. Furthermore, the local density normalisation of cool white dwarfs and hence their a-priori chance of having them in a volume-limited sample is  $(q_{\text{thin}}, q_{\text{thick}}, q_{\text{halo}}) = (0.69, 0.24, 0.07)$  (from Napiwotzki, private communication, based on Pauli et al. 2003). If cool white dwarfs are any guide to the currently unknown normalisations of ultra-cool objects, then thin disk membership would be more than 90% likely on the whole. We note, that thin and thick disk membership would only be equally probable, if the



**Fig. 3.** The SED of COMBO-17-J1143 (black data points) compared to the spectra of all known ultra-cool white dwarfs (grey lines) except for LHS 1402. COMBO-17 photometry is shown with horizontal error bars indicating filter width and vertical error bars representing the respective flux error. The spectra have been normalised with respect to the measured flux in the three filters  $B$ ,  $V$  and  $R$ . COMBO-17 J1143 is most similar to LHS 3250 and SDSS J0947.



**Fig. 4.** Finding chart for COMBO-17 J114356.08-0144032 taken from a 5-h *R*-band image obtained with WFI at the 2.2 m-telescope at La Silla in February 2000. The frame is 120'' on a side. North is up and East is on the left.

**Table 2.** Photometry of the white dwarf COMBO-17 J1143. A minimum photometric error of 0<sup>m</sup>.03 was assumed to take calibration uncertainties into account.

$\lambda_{\text{cen}}/fwhm$		Vega-mag	ABmag
365/36	<i>U</i>	22.65 ± 0.04	23.44
458/97	<i>B</i>	22.45 ± 0.03	22.34
538/89	<i>V</i>	21.86 ± 0.03	21.86
648/160	<i>R</i>	21.46 ± 0.03	21.67
857/147	<i>I</i>	21.60 ± 0.04	22.11
	<i>J</i>	<21.6	<22.57
418/27		22.70 ± 0.05	22.54
462/13		22.45 ± 0.03	22.29
486/31		22.15 ± 0.03	22.11
519/16		21.93 ± 0.03	21.89
572/25		21.71 ± 0.03	21.77
605/21		21.66 ± 0.03	21.79
645/30		21.45 ± 0.03	21.69
696/21		21.36 ± 0.03	21.65
753/18		21.38 ± 0.03	21.77
816/21		21.47 ± 0.04	21.96
857/15		21.66 ± 0.13	22.24
914/26		21.83 ± 0.06	22.35
$(g - r)_{\text{SDSS}}$		0.71 ± 0.12	
$(r - i)_{\text{SDSS}}$		-0.23 ± 0.17	
$(g - r)_{\text{COMBO-17}}$		0.53 ± 0.05	
$(r - i)_{\text{COMBO-17}}$		-0.12 ± 0.05	

distance was larger by a factor of  $\sim 2.5$ . Also, Gates et al. (2004) ruled out halo membership for most of their objects.

### 3.2. Spectral features

Unfortunately, the featureless spectra of ultra-cool dwarfs hold no prospect for measuring radial velocities or investigate

potential binarity. If the object was a double degenerate as it is assumed for LHS 3250 because of its luminosity of  $M_V = 15.7$ , this would affect the distance measurement.

The filter SED may suggest a somewhat surprising dent around 600 nm, but that may be a chance outlier. Among 17 filters, one filter measurement should be expected to deviate by  $\sim 1.8\sigma$  from the true flux purely by chance. Another similar dent in the spectrum of SDSS J1001 might not be real either given that the spectrum is rather noisy.

### 3.3. Surface densities

The recent SDSS search by Gates et al. (2004) found six objects in 4330  $\square^\circ$ , i.e. a surface density of 0.0014/ $\square^\circ$  with  $i < 20.2$ , which is roughly equivalent to  $R < 19.8$ . Given our  $\sim 3$  mag deeper selection, we still expect to find only one ultra-cool dwarf within roughly a couple hundred square degrees. Our small survey area of 0.78  $\square^\circ$  demonstrates that COMBO-17 contains an ultra-cool white dwarf at  $R < 23$  purely by chance.

This letter has reported another ultra-cool white dwarf, enlarging the sample of known cases to eight. Although, it is presumably the most distant example of its kind, it appears not particularly likely to belong to the Galactic thick disk or halo. We will need measurements of parallaxes to constrain the physical nature of these objects and proceed further to an understanding of their atmospheres. If spectral features were found and radial velocities and distances were measured, the kinematic properties of ultra-cool white dwarfs as a group could reveal clues about the stellar evolution channel responsible for their origin.

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