

New OB star candidates in the Carina Arm around Westerlund 2 from VPHAS+

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17 April 2015

ABSTRACT

O and early B stars are at the apex of galactic ecology, but in the Milky Way, only a minority of them may yet have been identified. We present the results of a pilot study to select and parametrise OB star candidates in the Southern Galactic plane, down to a limiting magnitude of $g = 20$. A 2 square-degree field capturing the Carina Arm around the young massive star cluster, Westerlund 2, is examined. The confirmed OB stars in this cluster are used to validate our identification method, based on selection from the $(u - g, g - r)$ diagram for the region. Our Markov Chain Monte Carlo fitting method combines VPHAS+ u, g, r, i with published J, H, K photometry in order to derive posterior probability distributions of the stellar parameters $\log(T_{\text{eff}})$ and distance modulus, together with the reddening parameters A_0 and R_V . The stellar parameters are sufficient to confirm OB status while the reddening parameters are determined to a precision of $\sigma(A_0) \sim 0.09$ and $\sigma(R_V) \sim 0.08$. There are 489 objects that fit well as new OB candidates, earlier than $\sim B2$. This total includes 74 probable massive O stars, 5 likely blue supergiants and 32 reddened subdwarfs. This increases the number of previously known and candidate OB stars in the region by nearly a factor of 10. Most of the new objects are likely to be at distances between 3 and 6 kpc. We have confirmed the results of previous studies that, at these longer distances, these sight lines require non-standard reddening laws with $3.5 < R_V < 4$.

Key words: stars: early-type, (Galaxy:) open clusters and associations: individual: Westerlund 2, (ISM:) dust, extinction, Galaxy: structure, surveys

1 INTRODUCTION

Stars of spectral type O and early B, more massive than $\sim 8M_{\odot}$, are massive enough to form collapsing cores at the end of their nuclear-burning lifetimes (see e.g. Langer 2012;

Smartt 2009). It is widely recognised that these stars - henceforward OB stars - are an important source of kinetic energy, driving turbulence and mixing of the interstellar medium, powered by a range of phenomena (stellar winds, wind-blown bubbles, expanding HII regions and supernova explosions). They are the main source of ultra-violet radiation in galaxies and, being short-lived ($\lesssim 40$ Myr), they are excellent tracers of recent star formation.

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In the Galaxy, clusters containing OB stars and OB associations have played an important role in tracing spiral arm structure (e.g. Russeil 2003; Vallée 2008). The typical scale height estimated for OB stars, forming in the Galactic disk, is a few 10s of pc (e.g. Reed 2000; Garmany et al. 1982), in keeping with estimates of the scale height for giant molecular clouds, their birth sites (e.g. Stark & Lee 2005). OB stars are usually regarded as forming in clustered environments (Zinnecker & Yorke 2007) and are less common in the field. However, examples of isolated field O stars are known and the question has arisen as to whether these high-mass stars have formed in situ, perhaps as the result of stochastic sampling of the initial mass function (IMF) as outlined by Parker & Goodwin (2007), or have been ejected from clusters as runaways (see e.g. Portegies Zwart et al. 2010; Bestenlehner et al. 2011). In the Milky Way $\sim 96\%$ of known O-type stars have been identified as members of young open clusters, OB associations or as otherwise kinematically linked to clustered environments (de Wit et al. 2005). This leaves up to $\sim 4\%$ of Galactic O-type stars possibly forming in isolation. Deep comprehensive searches for OB stars away from clusters have not been undertaken hitherto.

As luminous objects detected to great distances across the Galactic disk and through substantial obscuration, OB stars have long been recognised as a highly-suitable means for characterising the spatial variation of interstellar extinction, in terms of both dust column and extinction law (e.g. Cardelli et al. 1989; Fitzpatrick & Massa 2007). This is aided by their relatively simple optical near-infrared (OnIR) spectral energy distributions (SEDs). It follows from this that the more densely we can map the positions and extinctions towards these luminous probes, the more high-quality empirical constraints we can set on the 3-D distribution of dust and dust properties across the Galactic Plane.

Both of the above areas of enquiry will be well served by a deeper, more comprehensive mapping of the OB stars in the Milky Way. Past cataloguing efforts have been limited to brighter, nearer objects (e.g. Garmany et al. 1982; Reed 2003; Maíz-Apellániz et al. 2004). Indeed the most comprehensive collection so far, ‘The Catalog of Galactic OB Stars’ (Reed 2003) contains ~ 16000 known or suspected OB stars taken from across the literature: around 95% of the entries are brighter than 13th magnitude in the visual bands. Now is the right time to push the magnitude limit much fainter, to $\sim 20^{\text{th}}$ magnitude, given the likely delivery of astrometry to this depth by the Gaia mission from ~ 2017 onwards (both parallaxes *and* proper motions, for details on expected performance see de Bruijne 2012). Efficient, purely photometric selection of OB stars in the field as well as in clusters continues to be best undertaken at blue optical wavelengths, where colour selection via the *Q* method (initiated by Johnson & Morgan 1953a) is proven to separate O and early B stars from later type stars.

The practical motivation of this paper is to establish a method of photometric selection and analysis that can form the basis for a new homogeneous census of Galactic OB stars as faint as $g \simeq 20$. Based on a restrained extrapolation of the first results presented here, we can surmise that a new census will more than double the numbers known. A suitable source for the new census will be the VST Photometric H α Survey of the Southern Galactic Plane and Bulge (VPHAS+

Drew et al. 2014). VPHAS+ is a deep, uniform, photometric survey of the entire southern Galactic Plane and Bulge in broad-band *u*, *g*, *r*, *i* and narrow-band H α filters on ESO’s VLT Survey Telescope (VST). The survey footprint includes the entire southern Galactic Plane within the Galactic latitude range of $|b| < 5^\circ$. The VST’s OmegaCam imager provides a full square degree field of view with very good spatial resolution (0.2” pixels sample a median seeing of 0.8 – 1.0 arcsec in the *u/g/r* bands).

Here, we present a first study that uses broadband VPHAS+ data to select and parametrize OB stars in a ~ 2 square-degree area, roughly centred on $\ell = 284^\circ$, $b = -0.7^\circ$, in the part of the Plane containing the young massive cluster, Westerlund 2 (Wd 2), the larger associated HII region RCW 49, and the diffuse nebula NGC3199 (see Figure 1). Previous optical and near-infrared studies on the stellar content of Westerlund 2 have focused on the immediate environment of the cluster itself - a patch of sky 4 arcmin across - (Moffat et al. 1991; Ascenso et al. 2007; Vargas Álvarez et al. 2013), while the x-ray study by Tsujimoto et al. (2007) focused on an area ~ 17 arcmin across. Most recently, Hur et al. (2015) have revisited optical photometry of this cluster over a 17.9’ x 9.3’ footprint.

By tracing 8 μm warm-dust emission Rahman & Murray (2010) have identified this same region as part of a large star-forming complex (G283). On the sky, Wd 2 falls close to the Carina Arm tangent direction (e.g. Russeil 2003): the CO data presented by Dame (2007) show persuasively that Wd 2 and its environs fall just inside the sky position of the tangent point, but further away. This cluster is estimated to be 1 - 3Myr old (Vargas Álvarez et al. 2013; Ascenso et al. 2007). It contains a large number of spectroscopically-confirmed OB stars, albeit behind a dust column giving rise to over 6 magnitudes of visual extinction (Moffat et al. 1991; Rauw et al. 2007; Carraro et al. 2012; Vargas Álvarez et al. 2013). Estimates of the distance to Wd 2 in the literature have varied enormously, ranging from 2.8 kpc (Ascenso et al. 2007) up to ~ 8 kpc (e.g. Rauw et al. 2011). However, it is not our aim to enter into this debate. More important is the likelihood that much of the scientific gain from VPHAS+ discoveries of OB stars will be in the domain of visual extinctions of up to 8–10 magnitudes, and distance scales of 2–10 kpc (according to Galactic longitude). In this regard, the field around Wd 2 is highly typical of the task ahead.

A recent study on Wd 2 by Vargas Álvarez et al. (2013) uses data from the Hubble Space Telescope (HST) that offers much better spatial resolution than is achievable from the ground. This is the only dataset that offers better angular resolution than the new VPHAS+ data analysed here. These authors’ values of R_V and A_V were derived by fitting, to 32 individual OB stars in or near Wd 2, reddened model optical/near-infrared SEDs appropriate for the selected stars’ spectroscopically-confirmed spectral types. The best fits were computed by seeking the global chi-squared minimum among all plausible values of R_V and A_V - resulting in a mean outcome of $R_V = 3.77 \pm 0.09$ and $A_V = 6.51 \pm 0.38$ mag combining results from different reddening law prescriptions. We use a comparison of our OnIR SED fit results for this same set of OB stars to bench-mark our method.

This paper is organised as follows. In Section 2 more details on the data used for this study are given. Section 3

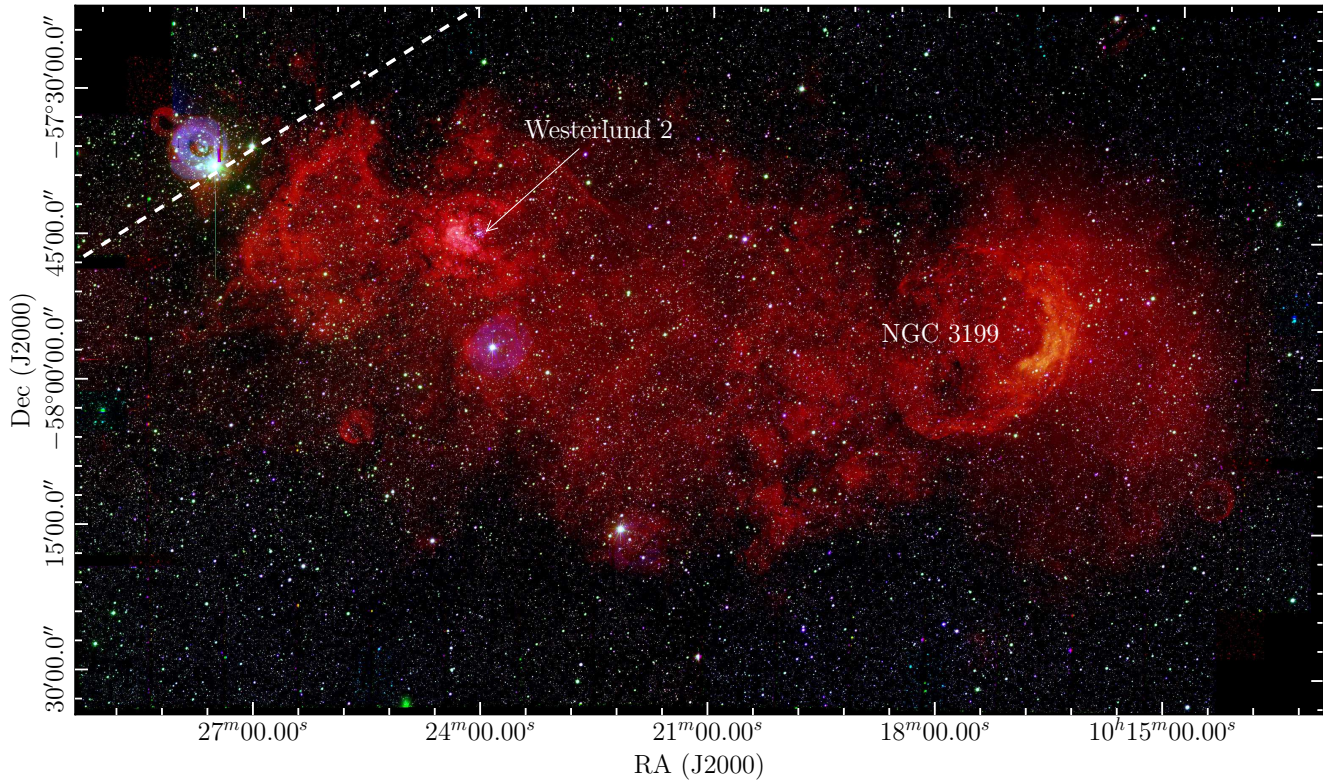


Figure 1. RGB image of the ~ 2 square degree region ($H\alpha$, g , i). This region falls within the star forming complex G283 identified by Rahman & Murray (2010) – an elliptical region slightly larger than the sky area shown. Westerlund 2 is embedded in the HII region RCW49, while the diffuse nebulae NGC3199 is located to the right (West) as marked. The dashed line traces the Galactic equator.

is a presentation of our method, beginning with the updated version of the Q method of OB star selection that we use, and ending with a description of the Markov Chain Monte Carlo (MCMC) sampling of the posterior distributions of the OnIR SED model fit parameters. The stage is then set to compare our results for Wd 2 stars with those of Vargas Álvarez et al. (2013), in Section 4. The results of the fits to the final list of 527 new OB candidates drawn from across the full 2 square degrees are presented in Section 5. This is followed by a discussion of the results in Section 6, in which we consider the extinction trends revealed in this region, and draw attention to the newly discovered O stars outside the confines of Wd 2. The outlook and our conclusions are summarised in Section 7.

2 THE DATA

We make use of the photometry from two VPHAS+ fields, numbered 1678 and 1679, that are respectively centred on RA 10 18 10.91, Dec -58 03 52.3 (J2000) and on RA 10 25 27.27, Dec -58 03 52.3 (J2000). These were observed in succession in the u , g and r filters on the night of 22nd January 2012. The red filter data in $H\alpha$, r and i were obtained on 29th April 2012. The seeing, as measured from the data point spread function, was variable on the earlier night ranging from 0.62 at best in g up to 1.24 at worst in r . When the exposures in the red filters were obtained 3 months later, conditions were more stable, with the typical

seeing ranging from 0.8 to 1.0 arcsec. Viewed in comparison to all the VPHAS+ data collected so far, these observations rank as 2nd-quartile quality in u and g (i.e. relatively high quality), and 3rd-quartile in r , i and $H\alpha$. The 5σ magnitude limits on the single exposures are u : 21.0, g : 22.4, r : 21.5, i : 20.6, and $H\alpha$: 20.4. All magnitudes are in the Vega system. Full details on the survey strategy, the offsets, the exposure times, photometric quality and the data-processing pipeline used are given by Drew et al. (2014).

Our analysis begins with band-merged catalogues created from the single-band catalogues emerging from the CASU pipeline. In order to correct for the uncertainty in the initial calibration of VPHAS+, a comparison has been made with empirical g , r and i observations from the APASS survey and with synthetic tracks in the $(u - g, g - r)$ plane. The median difference between g , r and i in the two surveys was applied to the VPHAS+ data. The u band was then calibrated by applying an offset to the $u - g$ scale such that the number density of stars between the synthetic G0V reddening track and the unreddened main sequence is maximised. This ensures that the top and bottom edge of the main stellar locus are aligned with the synthetic tracks as shown in Figure 2. This resulted in offsets relative to the pipeline reduction of u : -0.35, g : 0.05, r : 0.01 and i : 0.05 for field 1678 and u : -0.34, g : 0.06, r : 0.01 and i : 0.01 for field 1679. With an improved calibration in place, we select stars in the magnitude range $13 < g < 20$ and require random photometric errors to be less than 0.1. Mean magnitudes were taken when repeat photometry was available from the

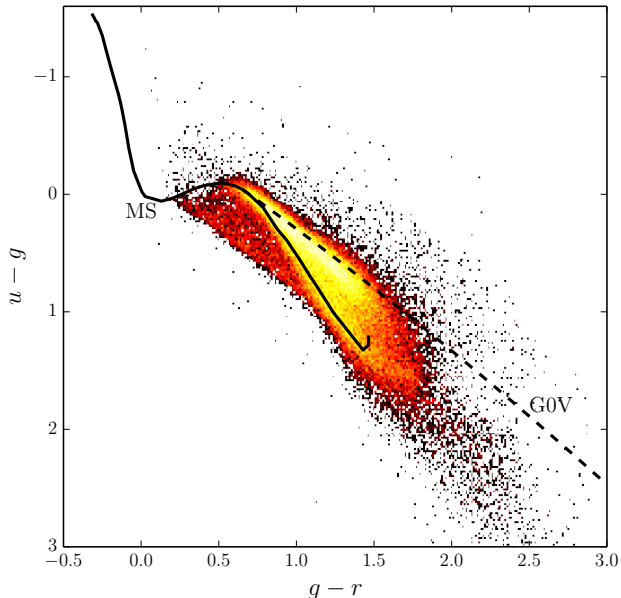


Figure 2. Calibration of VPHAS+ data with respect to synthetic reddening tracks from Drew et al. (2014). Both the main sequence and G0V reddening vector line up with the main stellar locus.

offset fields. Objects were removed if the photometry in the offset field differed by > 0.2 mags. This removes unreliable photometry due to objects that fall on a CCD edge.

3 SELECTION AND FITTING METHOD

3.1 Photometric selection and cross matching

We select OB stars using a method that has its origins in the Q Method of Johnson & Morgan (1953b). On the $(u - g, g - r)$ diagram reddened OB stars of spectral type earlier than B3 are located above and away from the main stellar locus. We initially select our candidate objects above the reddening vector associated with a B3V. In principle no star can be bluer than the Rayleigh-Jeans (RJ) limit which sets an upper bound on the likely location of OB stars in the diagram. The blue objects that lie above the RJ reddening vector were nevertheless included in the selection and their origins are discussed in section 5.

Figure 3 shows the selection of OB candidates (blue crosses) across the two fields as well as the known OB stars from Vargas Álvarez et al. (2013) that were successfully cross matched with VPHAS+ (shown as red triangles). Overplotted are the reddening tracks of a B3V, a B1V and that of a pure RJ spectrum all taken from Drew et al. (2014). The tracks we use take into account the measured red leak associated with the u -band filter.

Previous results from Carraro et al. (2012) and Vargas Álvarez et al. (2013) suggest an $R_V = 3.8$ reddening law is required towards Wd 2. The B1V and RJ reddening vectors have been drawn using this law. To avoid a bias towards this non-standard reddening law we have used the B3V $R_V = 3.1$ reddening vector as our lower selection limit and have dropped its position by 0.1 mags in $u - g$ in order to capture

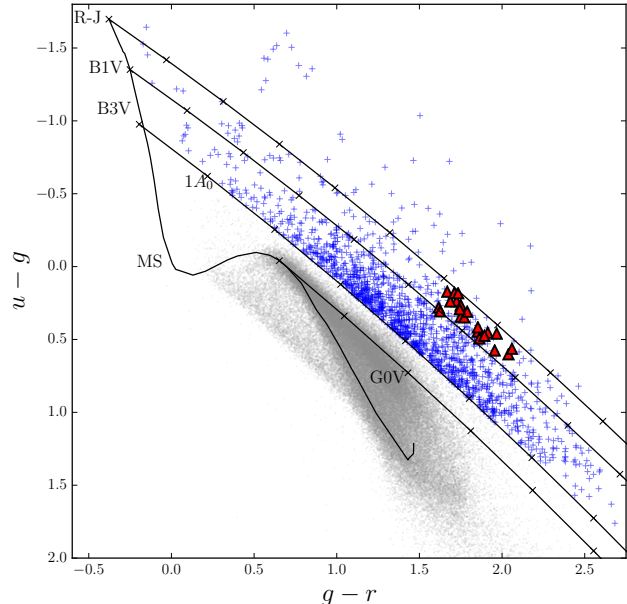


Figure 3. Selection of OB stars in and around Wd2. The lower reddening curve is that of a B3V, dropped by 0.1 in $u - g$ in order to capture all early type B stars, and is characterised by an $R_V = 3.1$ law. The other reddening curves are that of a B1V and an ideal Rayleigh-Jeans spectrum and are characterised by an $R_V = 3.8$ law. Selected OB candidates are blue crosses while the known objects from Vargas Álvarez et al. (2013) are red triangles.

any early B stars that may have been missed. The lower the value of R_V , the steeper the reddening vector will be.

Each object was then cross matched to within $1''$ of the best available near infra-red detection in order to access J, H, K photometry. The mean angular cross-match distance was $0.09''$. As the stellar density in the central $\sim 4'$ of Wd 2 is very high, the Ascenso et al. (2007) NIR catalogue was the preferred partner on account of its superior angular resolution. Everywhere else 2MASS was used. This follows the approach taken by Vargas Álvarez et al. (2013).

3.2 SED fitting

We calculate the probability distribution of a range of model parameters corresponding to a set of empirical measurements, in a Bayesian scheme. This approach is chosen over a straight forward χ^2 minimisation scheme so that we may recover the full posterior probability distribution. This can reveal covariance between different parameters.

Given a set of empirical data, $d = \{d_1, \dots, d_i\}$, and a model, parametrised by a set of parameters, $\theta = \{\theta_1, \dots, \theta_i\}$, the *posterior* probability of the parameters can be calculated using Bayes' Theorem:

$$P(\theta | d) = \frac{P(d | \theta) \cdot P(\theta)}{P(d)} \quad (1)$$

In this expression, $P(d | \theta)$, the *likelihood* is the probability of the data being measured given a set of model parameters. The *posterior* and the *likelihood* are related by the *prior*, $P(\theta)$, which encodes any known constraints on the model parameters, including known physical bounds. Here

$P(d)$ can be treated as a normalising constant and ignored. Hence the *posterior* probability distribution can be found by the relation:

$$P(\theta | d) \propto P(d | \theta) \cdot P(\theta) \quad (2)$$

In this work the empirical data are derived from the observed SED of each star and they consist of optical and near infrared apparent magnitudes:

$$SED_{obs} = \{u, g, r, i, J, H, K_S\}, \quad (3)$$

and their uncertainties:

$$\sigma(SED_{obs}) = \{\sigma_u, \sigma_g, \sigma_r, \sigma_i, \sigma_J, \sigma_H, \sigma_{K_S}\}. \quad (4)$$

Along with the random flux errors supplied by the surveys, we have included a systematic uncertainty to account for the independent absolute calibration errors in each band. The values adopted for the latter are 0.04 in the u band, 0.03 in g, r and i , 0.03 in the J band and 0.02 in H and K_S (see Drew et al. 2014; Skrutskie et al. 2006).

The model parameters that we are interested in estimating are:

$$\theta = \{\log(T_{\text{eff}}), A_0, R_V, \mu\} \quad (5)$$

Where $\log(T_{\text{eff}})$ is the effective temperature, A_0 is the monochromatic extinction at 4595Å, R_V is the ratio of total to selective extinction and μ is the distance modulus.

3.2.1 Likelihood function

Defining the likelihood function requires us to define a forward model $SED_{mod}(\theta)$, which predicts the apparent SED of OB stars based on the model parameters θ . The intrinsic SEDs used in the model are taken from the Padova isochrone database (CMD v2.2¹; Bressan et al. 2012; Bertelli et al. 1994) and are supplied in the Vega system. The optical/NIR colours of OB stars do not vary significantly with luminosity class (Martins et al. 2005). Therefore $\log(g)$ was fixed and only main-sequence models were used ($\log(g) \sim 4.0$). Solar metallicity $Z = 0.019$ has been adopted throughout, in view of the fact that the sight lines we explore do not sample a wide range of Galactic radii. This is the same value as used by Vargas Álvarez et al. (2013). Fixing these parameters provides a simple grid of absolute magnitude, M_λ , as a function of $\log(T_{\text{eff}})$ in each of the seven bands.

To obtain a continuous grid, each $M_\lambda - \log(T_{\text{eff}})$ relationship was fit with a 2^{nd} order polynomial. It can be noted that a linear fit was also trialled but failed to characterize the distributions especially for the low-end values of $\log(T_{\text{eff}})$. Table 1 provides sample SEDs.

The SEDs are then reddened using a Fitzpatrick & Massa (2007) reddening law, parametrised by A_0 and R_V , and then shifted according to a distance modulus. The apparent OnIR SEDs of O and early B stars are largely controlled by these quantities. This is because the OnIR intrinsic colours of OB stars change very slowly as a function of

Table 1. Sample values of the intrinsic SEDs with approximate spectral type equivalents. Magnitudes are in the Vega system.

ST	$\log(T_{\text{eff}})$	u	g	r	i	J	H	K_S
O3V	4.65	-7.32	-5.78	-5.48	-5.33	-4.88	-4.73	-4.63
O9V	4.50	-5.28	-3.86	-3.60	-3.45	-3.03	-2.90	-2.80
B1V	4.40	-3.97	-2.70	-2.47	-2.34	-1.98	-1.85	-1.77
B3V	4.27	-2.31	-1.33	-1.16	-1.07	-0.80	-0.70	-0.65

effective temperature (Martins et al. 2005), as the Rayleigh-Jeans limit is approached. This means that $\log(T_{\text{eff}})$ is only weakly constrained, albeit well enough to reach our goal of confirming OB status. As we have no handle on luminosity class, the distance modulus takes the role of a normalisation factor and will also be weakly constrained. In contrast A_0 and R_V are very informative and well constrained.

We can now use the forward model to construct a *likelihood* model $P(SED_{obs} | \theta)$ that computes the probability of SED_{obs} given the set of physical parameters θ . Assuming that the uncertainties on the measurements are normally distributed and uncorrelated, this can be described by a multi-variate Gaussian:

$$P(SED_{obs} | \theta) \propto \exp \left[-\frac{1}{2} (SED_{obs} - SED_{mod})^T \Sigma^{-1} (SED_{obs} - SED_{mod}) \right] \quad (6)$$

Where Σ is the covariance matrix containing the variance $\sigma^2(SED_{obs})$ in the leading diagonal. In this case Equation 6 reduces to the familiar sum for χ^2 :

$$P(SED_{obs} | \theta) \propto \exp \left(-\frac{1}{2} \sum_i^n \frac{(m(obs)_i - m(mod)_i)^2}{\sigma_i^2} \right) \quad (7)$$

Where $m(obs)_i$ and $m(mod)_i$ are the observed and model magnitudes in each band i .

3.2.2 Priors

We adopt a uniform *prior* on each of the model parameters:

$$P(\theta) = \begin{cases} 1 & \text{if } \begin{cases} 4.2 \leq \log(T_{\text{eff}}) \leq 4.7 \\ 0 \leq A_0 \leq 15 \\ 2.1 \leq R_V \leq 5.1 \\ 0 \leq \mu \leq 20 \end{cases} \\ 0 & \text{else} \end{cases} \quad (8)$$

The upper bound on $\log(T_{\text{eff}})$ is governed by the available models and the lower bound is slightly less than the typical temperature of a B3V star (Zorec & Briot 1991) in accordance with our selection in the $(u - g, g - r)$ diagram. The constraints on R_V are the upper and lower limits measured in the Galaxy (Fitzpatrick & Massa 2007). The upper limit on A_0 is much larger than maximum extinction allowed for detection of OB stars in VPHAS+ down to $g = 20$, assuming a typical rise in visual extinction of 1 magnitude per kpc. This makes the prior on A_0 essentially unbound. The upper limit on the distance modulus μ of 20 is well beyond the realms of the galaxy and so is also essentially unbound.

¹ <http://stev.oapd.inaf.it/cgi-bin/cmd>

Placing a large but finite limit on A_0 and μ enables the MCMC algorithm to converge more quickly.

3.2.3 Sampling the posterior distribution using MCMC

Characterising the *posterior* distribution by computing the probability at all values in the parameter space is computationally expensive. Instead one can sample the distribution using an MCMC algorithm.

In this study we use the Python package *emcee* developed by Foreman-Mackey et al. (2013). In brief, the software takes a set of parameters and supplies them to a group of n *walkers*. The *walkers* then use a pseudo-random walk to sample the parameter space. At each sample the probability is calculated. By communicating their relative probabilities to one another the *walkers* are able to quickly find and sample the region of high probability without wasting computational time on the parameter combinations of very low probability. The software then returns what are known as *chains* which contain the values of the parameters at every step in the walk. The frequency at which each region in the parameter space is visited is proportional to its probability. The finer details can be found in Foreman-Mackey et al. (2013).

4 VALIDATION OF METHOD

First it is appropriate to verify that our selection method recovers known objects. Second we verify that the fitting algorithm delivers the expected results. To achieve this, we have chosen to compare with the results of the recent study by Vargas Álvarez et al. (2013). This is an informative comparison to make both because this study benefited from the superior angular resolution of HST and because Vargas Álvarez et al. (2013) used a combination of optical and NIR photometry to derive stellar reddenings as we do here.

4.1 Photometric selection

Vargas Álvarez et al. (2013) derived the extinction properties of 29 known OB stars in the central region of Wd 2, of which, 24 were successfully cross matched with VPHAS+ to within $1''$. Using the nomenclature from Vargas Álvarez et al. (2013), the five missing objects are #597, #826, #843, #903 and #906. They appear in some of the most crowded regions of the cluster: the angular resolution of VPHAS+ compared to that of HST is insufficient to separate them from brighter neighbours. Figure 4 shows the positions of the 24 cross-matched objects and the positions of those that are missing (relative to Vargas Álvarez et al. 2013) over plotted on the g-band image.

Figure 5 is the highly magnified section of Figure 3 that contains the objects with known spectral type. The red and blue shaded regions are where we expect to find late-type (O9 - O6) and early-type (O6 - RJ) O stars respectively. We find that the majority of the objects are correctly separated into their respective early or late spectral-type zones defined by the $R_V = 3.8$ reddening tracks. This gives an early indication that an $R_V \sim 3.8$ reddening law is required for this sight-line and that the calibration of the data is in good agreement with the synthetic photometry.

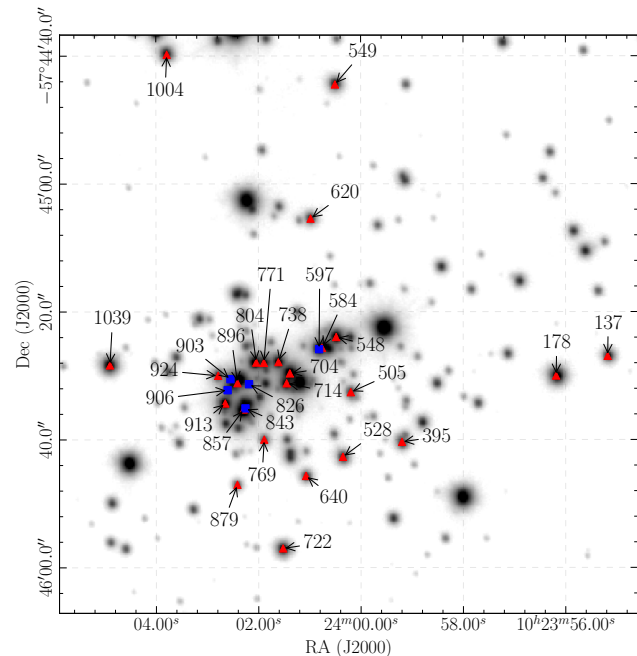


Figure 4. Inverse VPHAS+ g band image of the central region of Wd 2 showing the objects with known spectral type from Vargas Álvarez et al. (2013). The red triangles are the positions of the objects detected in VPHAS+ and the blue squares are the positions of those that are not detected due to crowding.

Object #771 falls well above the ‘RJ limit’. As a confirmed O8V star, its position in the $(u - g, g - r)$ diagram is clearly anomalous. Close inspection of the image suggests that the photometry of this star is affected by a bright neighbour.

4.2 SED fitting

Ultimately 21 of the 24 known objects were suitable for SED fitting. These objects are tabulated in Table 2. Two of the objects left out are #896 and #771 for which there is no detection in one or more of the optical bands due to blending. The third is object #1004 for which the near-infrared photometry is incomplete.

For each of the 21 objects for which we have computed SED fits, the posterior distribution was sampled with 100 *walkers* over 10000 *iterations* with a 1000 iteration burn in. The typical autocorrelation time for each walk (or number of steps per independent sample) was found to be well below 100, which indicates that the posteriors are thoroughly sampled. We can determine the probability distributions for each parameter by marginalising over all other parameters. We visualize this by constructing 1-D histograms of the values of each parameter visited in the random walk. We can also check for covariance or degeneracy between parameters by constructing marginalised 2-D histograms for each pair of parameters. Figure 6 shows an example of these diagrams for an O4V and a B1V star in the sample (#913 and #549).

The obvious difference between the two cases is apparent in the 1-D marginalisation of parameters. We see that the hotter the object the more skewed the probability distributions in $\log(T_{\text{eff}})$ and μ become. This can be attributed to

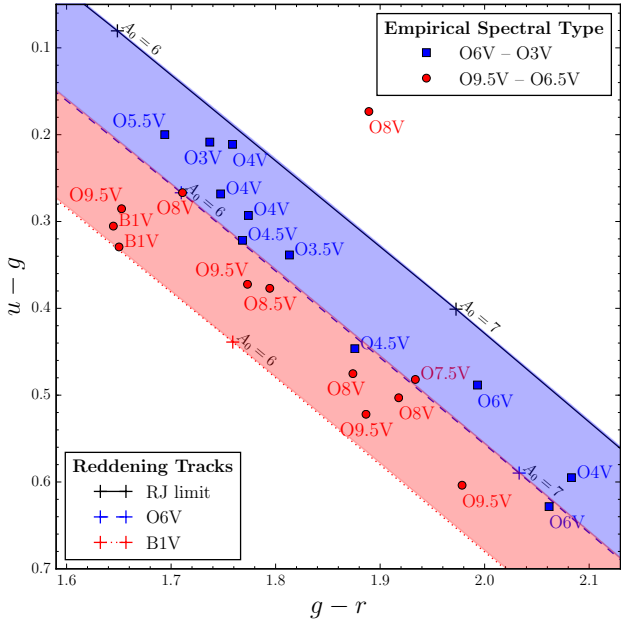


Figure 5. Testing the selection process of OB stars associated with Wd2. Objects with known spectral type tend to fall into the correct synthetic spectral type range with an $R_V = 3.8$ reddening law.

the fact that the hotter SEDs are approaching the RJ tail. This makes it more difficult to differentiate the temperature of the hottest stars and consequently the luminosity and distance. This makes the drop off in probability at the hot end more shallow. This intrinsic feature also means that the uncertainties on $\log(T_{\text{eff}})$ and μ increase with temperature but has the positive effect of decreasing the uncertainties on A_0 and R_V . For the later type stars $\log(T_{\text{eff}})$ is better defined but still uncertain.

The value adopted for each parameter is the median of the marginalised posterior distribution with upper and lower uncertainties defined by the 16th and 84th percentiles. We find that we are able to determine the values of A_0 and R_V with relatively high precision (better than ± 0.09 mag and ± 0.08 respectively in all cases). These uncertainties are similar to those found by Vargas Álvarez et al. (2013). We note that R_V and A_0 are well defined and show negligible covariance relative to each other and only modest covariance with respect to $\log(T_{\text{eff}})$ and μ .

However, as expected, our determination of temperature and distance are not so informative. For object #913, $\log(T_{\text{eff}}) = 4.61^{+0.06}_{-0.07}$ and $\mu = 13.23^{+0.78}_{-0.89}$. This corresponds to values of $T_{\text{eff}} = 40.7^{+6.0}_{-6.1}$ kK, or a spectral type range from O8V to O2V. The results for μ translate to $d = 4.4^{+1.9}_{-1.5}$ kpc. This already significant distance uncertainty is nevertheless an underestimate given that neither the luminosity class or metallicity uncertainties have been formally incorporated. In addition we are treating all stars as if single which biases the inferred distance moduli to lower values by up to 0.75 mag. Because of the relative lack of constraint on $\log(T_{\text{eff}})$ from the intrinsic colours of OB stars, the error in $\log(T_{\text{eff}})$ is driven mainly by the error in μ . In comparison the direct effect of binarity on $\log(T_{\text{eff}})$, through colour-changes, will be small. It is plainly apparent in Figure 6 that $\log(T_{\text{eff}})$

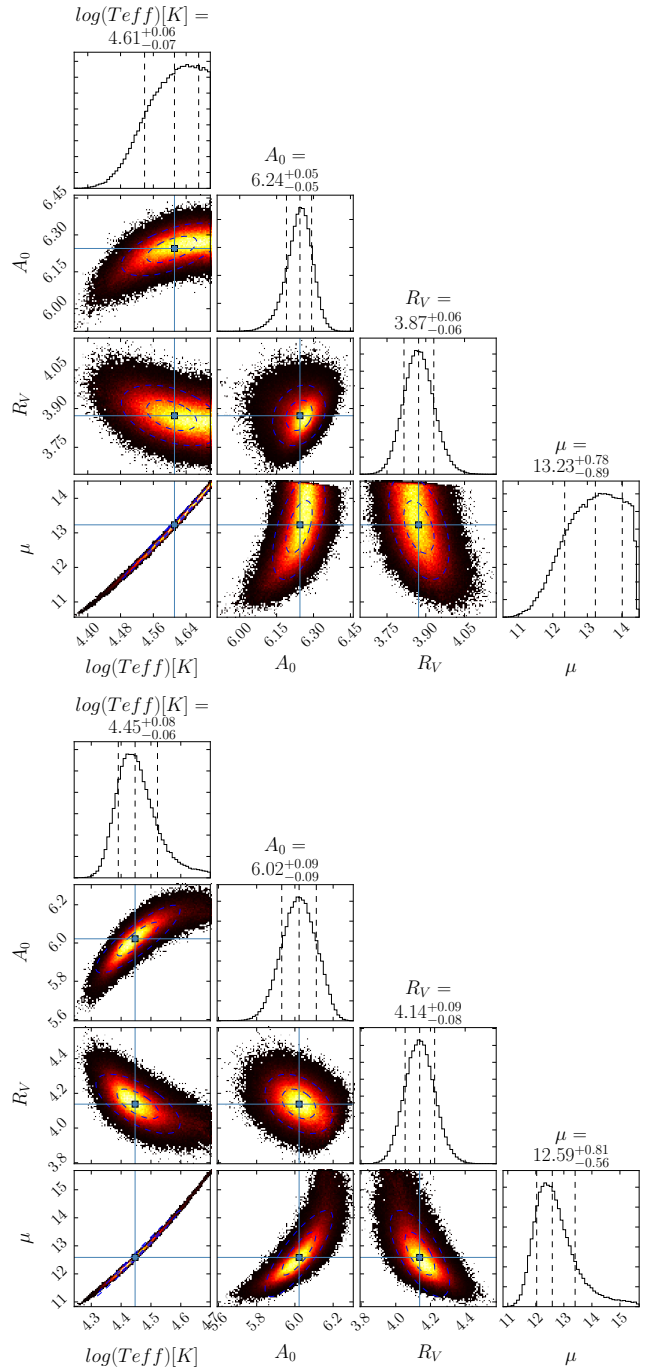


Figure 6. PDFs of the fitting parameters as a result of the MCMC simulation for stars #913 an O4V (top) and #549 and B1V (bottom) using the numbering system from Vargas Álvarez et al. (2013).

and μ are strongly and positively covariant. The role of the distance modulus is essentially that of a normalisation parameter.

Figure 7 shows the results for the O4V star from Figure 6 translated into the original SED data space. The top panel shows the observed SED over-plotted by 30 randomly sampled model SEDs that are drawn from the posterior distributions shown in Figure 6. The lower panel shows the residuals

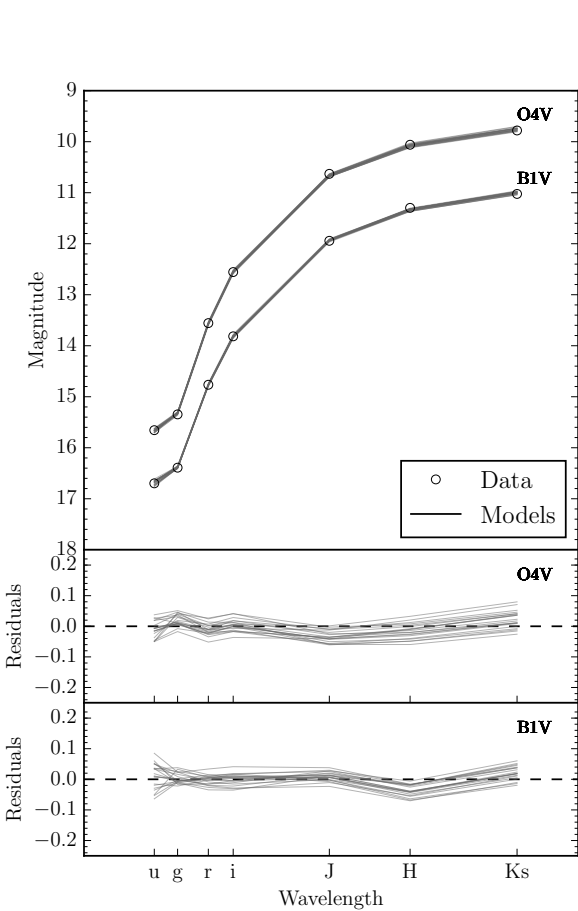


Figure 7. Visualisation of the posterior distributions of objects #913 and #549 (from Vargas Álvarez et al. 2013) in SED data space. The top panel shows 30 model SEDs for both objects (gray solid lines), generated from a random sampling of the posterior parameter distributions shown in Figure 6. Our photometric data is plotted on top (circles). The bottom panels show the residuals.

between them. We can see that for each band, across all the posterior distributions, the differences between the models and the data never exceed ~ 0.1 mag. The discrepancies between the model and data can be attributed to one or more of the following: inaccuracies in the intrinsic SEDs of OB stars in the Padova isochrones; inaccuracies in the shape of the reddening law; a calibration offset between the optical and NIR catalogues.

Table 2 compares the stellar parameters of the 21 known OB stars derived in this study with those from Vargas Álvarez et al. (2013). Here A_0 has been converted to A_V and the VPHAS+ g band magnitudes have been converted to V band using the Sloan to Johnson conversion from Lupton (2005)² for ease of comparison. We also note that our SED-derived $\log(T_{\text{eff}})$ values are compared to spectroscopic values where available (Vargas Álvarez et al. 2013; Rauw et al. 2007). Otherwise effective temperatures are derived from spectral types according to the temperature scales of

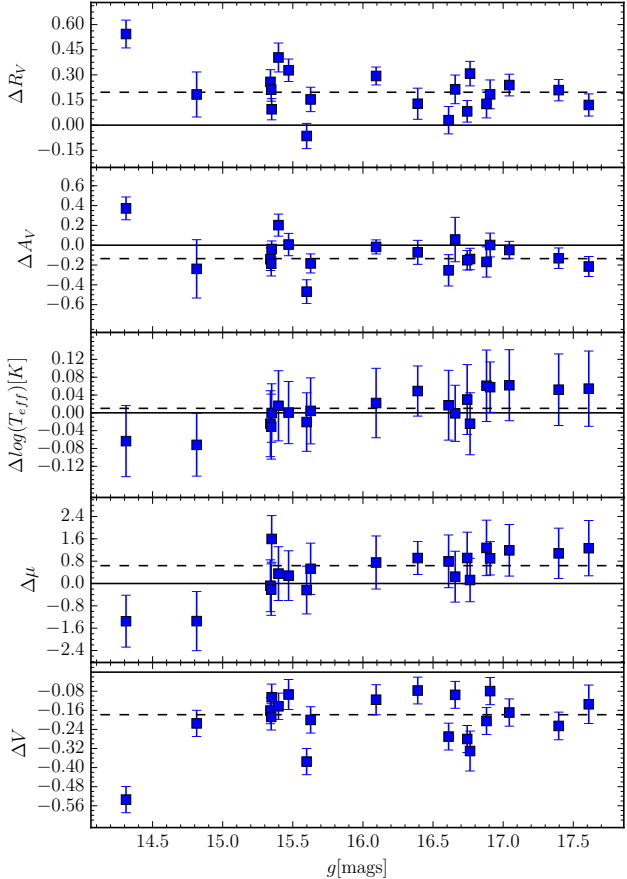


Figure 8. The difference between stellar parameters found in this study and those found by Vargas Álvarez et al. (2013). The solid line shows zero difference while the dashed line shows the median difference.

Martins et al. (2005) and Zorec & Briot (1991). We restrict our comparison to the results in Vargas Álvarez et al. (2013) based on the Fitzpatrick & Massa (2007) extinction curves.

Figure 8 plots the difference between the values derived in the two studies. It must be noted that star #584 has not been included in this analysis as extreme blending has substantially affected its photometry (see Figure 4 and Table 2).

A significant difference is found between the transformed V band magnitudes in VPHAS+ and HST of ~ 0.18 mag, such that VPHAS+ is brighter. Vargas Álvarez et al. (2013) compare their empirical B and V band measurements with those of Moffat et al. (1991) and Rauw et al. (2007) and find that those ground based measurements are also systematically brighter, by 0.18 and 0.15 mag, and by 0.22 and 0.12 respectively. Vargas Álvarez et al. (2013) suggest that the difference may be due to source blending following on from the effects of atmospheric seeing. If this were the case we would expect to find objects in the most crowded/blended region of the cluster to be consistently more discrepant. As we do not see this effect we suspect a real calibration difference. Hur et al. (2015) have also uncovered a similar problem but find good agreement between their optical photometry and that of Rauw et al. (2007). If

² <https://www.sdss3.org/dr8/algorithms/sdssUBVRITransform.php>

Table 2. Table comparing the derived stellar parameters of objects with known spectral type from Vargas Álvarez et al. (2013) with the results in this study. The ID given corresponds to the numeration given by Vargas Álvarez et al. (2013). Most of the effective temperatures in the HST column were derived spectroscopically by Vargas Álvarez et al. (2013) and uncertainties were given. The rest have no provided uncertainty as they were estimated from their spectral types using the temperature scales from Martins et al. (2005) and Zorec & Briot (1991).

ID	ST	A_V		R_V		$\log(T_{\text{eff}})$		μ		V	
		VPHAS+	HST	VPHAS+	HST	VPHAS+	HST	VPHAS+	HST	VPHAS+	HST
137	O4 V	$7.47^{+0.04}_{-0.04}$	7.41 ± 0.22	$4.05^{+0.05}_{-0.05}$	3.84 ± 0.07	$4.63^{+0.05}_{-0.06}$	4.633 ± 0.004	$13.43^{+0.62}_{-0.79}$	13.19 ± 0.45	$15.496 \pm +0.056$	15.591 ± 0.006
178	O4 V-III((f))	$6.34^{+0.04}_{-0.04}$	6.38 ± 0.07	$4.03^{+0.06}_{-0.06}$	3.93 ± 0.03	$4.63^{+0.05}_{-0.07}$	4.629 ± 0.002	$13.38^{+0.64}_{-0.82}$	11.79 ± 0.16	$14.385 \pm +0.055$	14.490 ± 0.004
395	O7.5V	$6.78^{+0.07}_{-0.08}$	6.92 ± 0.07	$4.08^{+0.07}_{-0.07}$	3.77 ± 0.03	$4.52^{+0.09}_{-0.07}$	4.544 ± 0.000	$12.91^{+1.09}_{-0.76}$	12.78 ± 0.18	$15.688 \pm +0.056$	16.019 ± 0.062
505	O8.5V	$6.19^{+0.05}_{-0.06}$	6.36 ± 0.14	$3.84^{+0.06}_{-0.06}$	3.71 ± 0.06	$4.59^{+0.07}_{-0.08}$	4.531 ± 0.006	$14.57^{+0.93}_{-0.95}$	13.29 ± 0.30	$15.889 \pm +0.056$	16.094 ± 0.005
528	O8 V	$6.72^{+0.06}_{-0.07}$	6.97 ± 0.14	$4.02^{+0.07}_{-0.06}$	3.99 ± 0.05	$4.56^{+0.09}_{-0.08}$	4.544 ± 0.005	$13.34^{+1.10}_{-0.89}$	12.55 ± 0.30	$15.571 \pm +0.056$	15.841 ± 0.005
548	O4 V	$6.34^{+0.05}_{-0.05}$	6.48 ± 0.10	$4.02^{+0.06}_{-0.06}$	3.76 ± 0.04	$4.61^{+0.06}_{-0.07}$	4.633 ± 0.002	$13.11^{+0.81}_{-0.90}$	13.19 ± 0.23	$14.361 \pm +0.055$	14.522 ± 0.002
549	B1 V	$6.02^{+0.09}_{-0.09}$	6.09 ± 0.08	$4.14^{+0.09}_{-0.08}$	4.01 ± 0.04	$4.45^{+0.08}_{-0.06}$	4.398 ± 0.000	$12.59^{+0.81}_{-0.56}$	11.68 ± 0.19	$15.485 \pm +0.056$	15.562 ± 0.005
584	O8 V	$4.60^{+0.04}_{-0.04}$	6.19 ± 0.05	$2.91^{+0.04}_{-0.04}$	3.73 ± 0.02	$4.66^{+0.03}_{-0.05}$	4.544 ± 0.002	$15.24^{+0.42}_{-0.64}$	12.94 ± 0.12	$14.195 \pm +0.055$	15.442 ± 0.004
620	B1 V	$5.77^{+0.09}_{-0.09}$	5.77 ± 0.08	$4.00^{+0.08}_{-0.08}$	3.82 ± 0.04	$4.46^{+0.08}_{-0.06}$	4.398 ± 0.000	$13.46^{+0.86}_{-0.56}$	12.56 ± 0.19	$16.007 \pm +0.057$	16.086 ± 0.006
640	O9.5V	$6.32^{+0.05}_{-0.07}$	6.37 ± 0.05	$3.97^{+0.07}_{-0.06}$	3.73 ± 0.02	$4.57^{+0.08}_{-0.08}$	4.505 ± 0.002	$14.30^{+1.07}_{-0.91}$	13.11 ± 0.13	$16.065 \pm +0.057$	16.234 ± 0.006
704	O4 V	$6.03^{+0.05}_{-0.05}$	6.27 ± 0.29	$3.94^{+0.06}_{-0.06}$	3.76 ± 0.12	$4.61^{+0.06}_{-0.07}$	4.681 ± 0.008	$12.91^{+0.77}_{-0.85}$	14.26 ± 0.63	$13.844 \pm +0.055$	14.059 ± 0.002
714	O3 V	$5.61^{+0.04}_{-0.05}$	6.08 ± 0.11	$3.67^{+0.06}_{-0.06}$	3.73 ± 0.05	$4.62^{+0.05}_{-0.07}$	4.643 ± 0.000	$14.29^{+0.69}_{-0.82}$	14.53 ± 0.26	$14.642 \pm +0.055$	15.017 ± 0.003
722	O6 V	$7.21^{+0.05}_{-0.06}$	7.23 ± 0.04	$3.94^{+0.06}_{-0.05}$	3.65 ± 0.01	$4.61^{+0.06}_{-0.08}$	4.584 ± 0.001	$12.79^{+0.84}_{-0.94}$	12.04 ± 0.11	$14.944 \pm +0.055$	15.060 ± 0.030
738	O5.5V	$5.84^{+0.05}_{-0.05}$	6.02 ± 0.08	$3.88^{+0.06}_{-0.06}$	3.73 ± 0.04	$4.61^{+0.06}_{-0.07}$	4.602 ± 0.000	$13.91^{+0.81}_{-0.90}$	13.39 ± 0.19	$14.696 \pm +0.055$	14.896 ± 0.003
769	O9.5V	$6.50^{+0.06}_{-0.09}$	6.63 ± 0.06	$3.86^{+0.07}_{-0.06}$	3.65 ± 0.02	$4.54^{+0.10}_{-0.08}$	4.491 ± 0.002	$14.12^{+1.20}_{-0.89}$	13.04 ± 0.13	$16.351 \pm +0.057$	16.576 ± 0.008
804	O6 III	$7.11^{+0.11}_{-0.11}$	6.91 ± 0.04	$4.11^{+0.09}_{-0.09}$	3.71 ± 0.01	$4.60^{+0.07}_{-0.08}$	4.582 ± 0.001	$12.14^{+0.89}_{-0.96}$	11.78 ± 0.10	$14.290 \pm +0.055$	14.433 ± 0.003
857	O4.5V	$6.50^{+0.08}_{-0.08}$	6.13 ± 0.08	$4.17^{+0.09}_{-0.08}$	3.63 ± 0.03	$4.56^{+0.09}_{-0.08}$	4.623 ± 0.002	$11.30^{+1.08}_{-0.91}$	12.65 ± 0.18	$13.335 \pm +0.055$	13.869 ± 0.003
879	O9.5V	$6.77^{+0.06}_{-0.07}$	6.98 ± 0.07	$3.82^{+0.06}_{-0.06}$	3.70 ± 0.03	$4.57^{+0.08}_{-0.08}$	4.519 ± 0.003	$14.37^{+1.05}_{-0.98}$	13.11 ± 0.16	$16.510 \pm +0.058$	16.645 ± 0.056
913	O3-4V	$6.23^{+0.05}_{-0.06}$	6.42 ± 0.11	$3.87^{+0.06}_{-0.06}$	3.66 ± 0.04	$4.61^{+0.06}_{-0.07}$	4.642 ± 0.002	$13.23^{+0.78}_{-0.89}$	13.45 ± 0.24	$14.344 \pm +0.055$	14.531 ± 0.002
924	O8 V	$6.25^{+0.06}_{-0.07}$	6.40 ± 0.07	$3.68^{+0.06}_{-0.06}$	3.60 ± 0.03	$4.57^{+0.08}_{-0.08}$	4.544 ± 0.000	$14.08^{+1.02}_{-0.91}$	13.16 ± 0.16	$15.680 \pm +0.056$	15.960 ± 0.005
1039	O4-5V	$6.43^{+0.05}_{-0.05}$	6.42 ± 0.10	$3.80^{+0.06}_{-0.05}$	3.47 ± 0.04	$4.62^{+0.05}_{-0.07}$	4.622 ± 0.002	$13.26^{+0.70}_{-0.86}$	12.98 ± 0.22	$14.429 \pm +0.055$	14.523 ± 0.030

the scale of Rauw et al. (2007) is the right one, our photometry may be too bright by ~ 0.05 mag.

The apparent systematic calibration difference between the two data sets is reflected in the derived values of A_V . In particular the median of the star-by-star differences in A_V shows that our extinctions are on average 0.14 mag less than those derived by Vargas Álvarez et al. (2013). The median A_V with the 16th and 84th percentiles in this study and in Vargas Álvarez et al. (2013) are; $A_V(\text{VPHAS+}) = 6.34^{+0.32}_{-0.44}$ and $A_V(\text{HST}) = 6.41^{+0.32}_{-0.56}$. With brighter optical magnitudes there is also an offset in R_V such that our values are higher: the median star-by-star difference in R_V is 0.20, while sample medians are respectively $R_V(\text{VPHAS+}) = 3.96^{+0.14}_{-0.12}$ and $R_V(\text{HST}) = 3.73^{+0.08}_{-0.11}$.

Despite the expectation of poor constraints on distance, the difference in the median values of μ happen to be very small: $\mu(\text{VPHAS+}) = 13.36^{+0.57}_{-0.92}$ and $\mu(\text{HST}) = 13.07^{+1.02}_{-0.31}$. This is likely to be due to the O stars in Wd 2 being on the main sequence, matching our assumption. Similarly there is only a modest offset on average in the measures of effective temperature.

The results of this comparison are encouraging. We have found good quantitative agreement, within the uncertainties, between our derived parameters and those of Vargas Álvarez et al. (2013) drawing on HST optical photometry. Where there are differences, we understand their origin. This gives us confidence that both our method and the underlying VPHAS+ data are producing reliable results.

5 RESULTS

Here we apply the SED fitting methods discussed above to the full selection of OB candidates from our pilot ~ 2 sq.deg field.

5.1 ‘Goodness-of-fit’

The posterior distributions obtained tell us the most probable parameters given the data, however they do not tell us anything about ‘goodness-of-fit’. As some objects in our selection may be contaminants or may just have bad photometry, it is important to determine how well the data fit the model in order to obtain a ‘clean’ selection of OB stars. We have opted to use the value of χ^2 , given by the SED fits, at the median values in the marginalised posterior distribution. We are aware that the posterior medians may not exactly trace the maximum likelihood, but they provide a representative sample.

Figure 9 shows the χ^2 distribution of the fits to all 1050 objects in the wider selection above the distribution obtained for the known objects from Vargas Álvarez et al. (2013). Since we are fitting 7 data points with 4 parameters we expect a $k = 3$ χ^2 distribution peaking at 1 – the top panel of Figure 9 indicates this is what happens and, by implication, that the uncertainties on our data points are not significantly over- or under- estimated. In keeping with this, we have chosen to use the commonly adopted 5% significance level, at $\chi^2 = 7.82$ as the limit beyond which

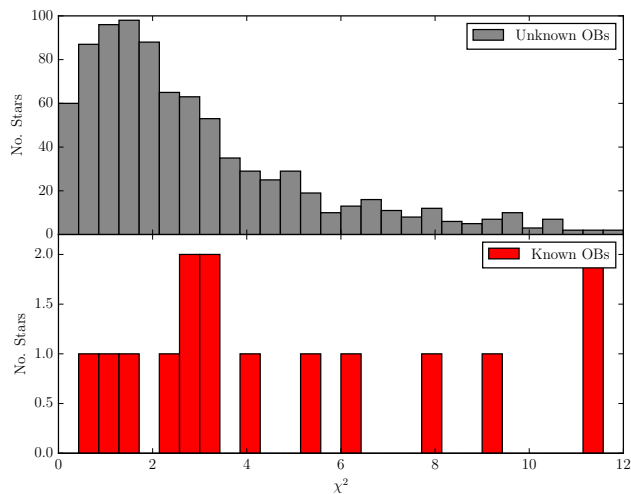


Figure 9. χ^2 distributions for the known objects (bottom) and the wider selection (top). The χ^2 distribution for the wider selection peaks at ~ 1 as expected from a distribution with $k = 3$ degrees of freedom. Using a 5% significance level we judge objects with $\chi^2 > 7.82$ to be unsatisfactorily fit. The known objects with poor fits are subject to photometric blending in the cluster’s core.

we judge the fits to the applied model to be unsatisfactory. This cut makes reasonable sense when applied to the χ^2 distribution for the known objects (in common with Vargas Álvarez et al. 2013), in that the 10 confirmed OB stars beyond the chosen cut are mainly there because of the impact on the photometry of the blending in the crowded central parts of Wd 2 present in the VST data. For this reason we have still tabulated those objects not meeting our selection criteria but have not used them in any further analysis. We note that if both 2MASS Skrutskie et al. (2006) and Ascenso et al. (2007) photometry are available we keep which ever yields a better χ^2 .

5.1.1 Further cross-matches with previously catalogued objects

All of the objects in the initial selection were cross-matched to $< 1''$ with the SIMBAD (Wenger et al. 2000) database to check for further examples of objects of known type.

Tsujimoto et al. (2007) conducted a 17×17 arcmin high resolution X-ray imaging survey centred on Wd2 and the surrounding star forming region RCW 49. They identified 17 new X-ray emitting OB candidates in this larger region, enclosing that studied by Vargas Álvarez et al. (2013). On using a $1''$ cross match radius we find 8 of these objects make it into our selection. Five of the missing objects are picked up by VPHAS+ but have $g < 13$ and hence were too bright to be selected. Conversely, the remaining 4 objects are detected by VPHAS+ but are too faint ($g > 20$) to be in our selection. It is likely that these objects are highly reddened.

Across all other literature sources, accessed via SIMBAD, fourteen further stars of confirmed type were found (see Table 3). The breakdown of their classifications is as follows: six stars with a Wolf-Rayet (WR) component, three OV, two OIII, one OVb, one B5Vne, one carbon star and

one star listed as M1III. All six WR stars, the carbon star and one of the OV stars could not be fitted convincingly as reddened OB stars (i.e. $\chi^2 > 7.82$), while the others were ($\chi^2 < 7.82$). The OVb was confirmed as an O3V + O5.5V binary system by Vargas Álvarez et al. (2013) but was not used in their SED fitting analysis – hence it did not feature in Section 4.2. On close inspection of the literature, it became clear that the SIMBAD M1III attribution matching one of our selected objects is wrong, resulting from confusion over the sky position of the previously catalogued HAeBe candidate, THA 35-II-41. THA 35-II-41 is indeed one of our selected objects but it is not at the position attributed to it by Carmona et al. (2010) where these authors observed an M giant spectrum.

We also detect seven bright objects in the originally NIR selected open cluster DBS2003 45 (Dutra et al. 2003) centred at $10\text{h}19\text{m}10.5\text{s} -58^\circ 02' 22.6''$. The study by Zhu et al. (2009) identifies seven OB stars in this cluster estimated as ranging from spectral type B0 to O7 from low resolution NIR spectroscopy. However, six out of seven of the positions given in Table 2 of Zhu et al. (2009) do not match with the VPHAS+ positions nor with any detections in the 2MASS point source catalogue. We therefore suspect that there is an error in the positions that they give whilst our objects are in common. We find these are among the most highly extinguished objects in our selection with an average $A_V = 8.37$.

5.1.2 Summary of results

Figure 10 shows the stages in the selection process: first, those stars without a match to good quality NIR photometry have to be set aside (shown as grey crosses in the Figure); next, those with ‘poor’ χ^2 values (the cyan-coloured squares); finally the good fits are divided in two groups based on their effective temperature. Those with a median posterior effective temperature exceeding 20000K, or equivalently $\log(T_{\text{eff}}) \geq 4.3$, are shown as red triangles while those that are assigned cooler fits are shown as blue squares. The hotter stars are our target group of spectral type B2 and earlier.

Counter-intuitively perhaps, it can be seen in Figure 10 that in the domain where $g - r < 0.5$, only 12 stars could be matched with good NIR photometry. This is because lowly reddened UV-excess objects detected in VPHAS+ are commonly too faint for detection in 2MASS due to their blue SEDs – for instance, some of these objects will be under-luminous hot compact objects. Unsurprisingly the cyan coloured squares representing objects with poor fits are frequently to be found above the Rayleigh-Jeans limit – only 2 objects with accepted fits fall into this part of the diagram. It is reassuring that there is some offset between the $R_V = 3.1$ B3V reddening vector, serving as lower bound to the selection region, and the spread of hotter objects: it suggests that few, if any, stars hotter than $\log(T_{\text{eff}}) = 4.3$ have been missed (given our other constraints, such as the magnitude limits). It is worth noting that the selection of objects that occupied the 0.1 mag wide band directly below the B3V reddening vector in $u - g$ provided just 1 star out of 374 with $\log(T_{\text{eff}}) \geq 4.3$ and $\chi^2 < 7.82$.

The main groupings emerging from the fitting process of all 1073 objects are shown in table 4. All of the objects along with their photometry and derived parameters are tabulated in Tables 5 and 6.

Table 3. Objects crossed matched with SIMBAD in the selection which have known spectral type. Derived parameters of highly evolved objects will be inaccurate due to the main-sequence assumption as shown by their large χ^2 values. On further inspection of the literature the classification object #895 is much different from that in SIMBAD(see Section)

ID	RA	DEC	Identifier	Spectral Type	g	$\log(T_{eff})$	R_V	A_0	μ	χ^2
282	10 18 04.98	-58 16 26.27	WR 19	WC5+O9	14.02	$4.37^{+0.05}_{-0.04}$	$5.79^{+0.09}_{-0.09}$	$4.14^{+0.09}_{-0.08}$	$9.60^{+0.48}_{-0.38}$	39.60
335	10 18 53.39	-58 07 52.94	WR 19a	WN	15.45	$4.54^{+0.10}_{-0.08}$	$8.59^{+0.06}_{-0.09}$	$4.32^{+0.07}_{-0.06}$	$9.87^{+1.19}_{-0.89}$	10.21
437	10 20 17.50	-57 44 59.39	C* 1665	C*	16.54	$4.66^{+0.02}_{-0.03}$	$12.30^{+0.04}_{-0.04}$	$4.54^{+0.03}_{-0.03}$	$8.05^{+0.32}_{-0.39}$	436.47
560	10 22 05.75	-57 53 46.03	2MASS J10220574-5753460	B5Vne	15.71	$4.42^{+0.07}_{-0.05}$	$5.64^{+0.09}_{-0.09}$	$3.80^{+0.07}_{-0.07}$	$11.98^{+0.68}_{-0.49}$	1.53
644	10 23 23.50	-58 00 20.80	SS 215	O2IF*/WN5	13.48	$4.41^{+0.06}_{-0.05}$	$5.67^{+0.09}_{-0.09}$	$4.27^{+0.10}_{-0.09}$	$9.60^{+0.57}_{-0.44}$	16.06
687	10 23 58.01	-57 45 48.93	V* V712 Car	O3IF*/WN6+O3IF*/WN6	14.48	$4.48^{+0.08}_{-0.06}$	$7.50^{+0.08}_{-0.09}$	$4.27^{+0.07}_{-0.07}$	$9.39^{+0.91}_{-0.63}$	10.47
717	10 24 01.20	-57 45 31.03	Cl* Westerlund 2 MSP 188	O3V+O5.5V	14.34	$4.53^{+0.10}_{-0.08}$	$6.79^{+0.09}_{-0.09}$	$4.41^{+0.10}_{-0.09}$	$10.70^{+1.19}_{-0.88}$	5.69
743	10 24 02.44	-57 44 36.05	Cl Westerlund 2 5	O5/5.5V/III(f)	13.80	$4.54^{+0.09}_{-0.07}$	$5.95^{+0.06}_{-0.08}$	$4.24^{+0.09}_{-0.08}$	$11.18^{+1.08}_{-0.81}$	10.56
770	10 24 06.64	-57 47 15.88	Cl* Westerlund 2 NRM 3	O9.5V	17.61	$4.58^{+0.08}_{-0.08}$	$7.75^{+0.05}_{-0.07}$	$4.14^{+0.06}_{-0.05}$	$13.44^{+1.03}_{-0.98}$	2.07
789	10 24 16.25	-57 43 43.75	Cl* Westerlund 2 NRM 2	O8.5III	15.94	$4.62^{+0.05}_{-0.07}$	$7.38^{+0.04}_{-0.05}$	$4.02^{+0.05}_{-0.05}$	$12.73^{+0.68}_{-0.87}$	2.47
793	10 24 18.40	-57 48 29.77	WR 20b	WN6ha	14.61	$4.38^{+0.06}_{-0.05}$	$7.97^{+0.09}_{-0.10}$	$4.60^{+0.08}_{-0.07}$	$7.94^{+0.55}_{-0.43}$	22.34
797	10 24 21.29	-57 47 27.53	Cl* Westerlund 2 NRM 1	O6V	15.70	$4.64^{+0.04}_{-0.06}$	$7.04^{+0.04}_{-0.04}$	$4.14^{+0.06}_{-0.05}$	$13.12^{+0.55}_{-0.76}$	3.59
822	10 24 39.20	-57 45 21.20	2MASS J10243919-5745211	O5V	16.03	$4.61^{+0.06}_{-0.08}$	$7.03^{+0.04}_{-0.05}$	$4.00^{+0.06}_{-0.05}$	$13.10^{+0.77}_{-0.93}$	1.68
895	10 25 47.07	-58 21 27.66	THA 35-II-41	HAeBe	13.55	$4.56^{+0.09}_{-0.08}$	$4.14^{+0.05}_{-0.07}$	$4.78^{+0.15}_{-0.13}$	$13.31^{+1.08}_{-0.87}$	4.89
907	10 25 56.51	-57 48 43.54	WR 21a	WN+	13.62	$4.37^{+0.05}_{-0.04}$	$6.34^{+0.09}_{-0.09}$	$4.45^{+0.09}_{-0.09}$	$8.59^{+0.49}_{-0.39}$	42.02

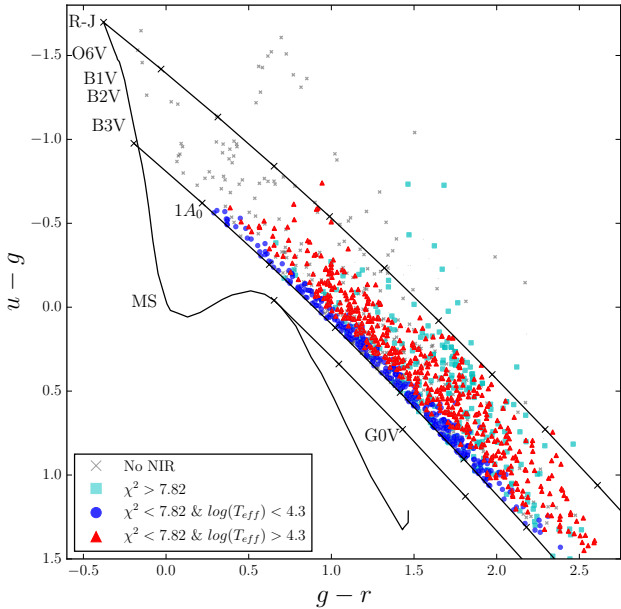


Figure 10. $(u-g, g-r)$ diagram showing the stages of selection. Red triangles are the final selection used for further discussion. All of the objects clearly above the RJ reddening vector are returned as bad fits.

5.1.3 Contaminants

The ($\chi^2 > 7.82$) fits have a range of causes. The most frequent are likely to be contact binaries or the products of poor photometry.

Contact binaries may find their way into the selection because they are both quite common and rapidly variable. Figure 11 shows how around half of the $\chi^2 \leq 7.82$ objects clearly separate in the $(r-i, g-r)$ colour-colour diagram away from the OB stars towards redder $g-r$ at fixed $r-i$. This is plausibly the signature of contact binary (W UMa) interlopers. W UMa systems are doubly eclipsing binaries in which the brightness in any one band scarcely remains con-

Table 4. Breakdown of the number of new OB candidates, previously identified OB candidates and objects with known spectral type according to effective temperature and fit quality.

All Objects: 1073			
	$\log(T_{eff}) \geq 4.3$	$\chi^2 \leq 7.82$	$\chi^2 > 7.82$
Total	527	145	
New Candidate OBs	489	98	
Old Candidate OBs	19	28	
Known O - B2 stars	19	10	
Other	0	1 C star & 6 WR stars	
	$\log(T_{eff}) < 4.3$	$\chi^2 \leq 7.82$	$\chi^2 > 7.82$
Total	321	80	
New Candidate OBs	320	78	
Old Candidate OBs	0	2	
Known O - B2 stars	1	0	
All $\log(T_{eff})$	848	225	

stant over time. These objects have typical orbital periods of 8 hours with two pronounced minima per cycle (Rucinski 1992). The $u/g/r$ VST exposures are taken sequentially with about 15 minutes elapsing between u and g , and g and r . If the g band exposure of a W UMa system is taken at or near minimum light, its measured $u-g$ colour is bluer than true, while $g-r$ is redder, potentially pushing the star up into our OB selection. However these objects fail to pass as OB stars when the whole OnIR SED fit is performed, hence their poor χ^2 values. It has been estimated that there is around 1 W UMa system for every ~ 130 main sequence stars (Rucinski 1992). So finding perhaps as many as ~ 100 in our OB selection, given ~ 100000 stars across the 2 square degrees with $u/g/r$ photometry, is reasonable.

The second common origin for the poor fits is likely due to photometry affected by blending or incorrect cross-matching between bands. In the crowded core of Wd 2 this is an obvious difficulty (see Figures 4 and 10).

The literature search already reported in section 5.1.2

Table 5: Sample table containing the positions and photometry of all 1073 objects. The first five columns are the objects IDs given in this study, VPHAS ID, Moffat et al. (1991), MSP ID, Vargas Álvarez et al. (2013), VA ID, T Fujimoto et al. (2007), TFFT ID, and in SIMBAD, SIMBAD ID, where applicable. The full table can be found in the electronic version of this paper.

ID	MSP ID	VA ID	TFFT ID	SIMBAD ID	ST	RA (J2000)	DEC (J2000)	u	err u	g	err g	r	err r	i	err i	Ha	err Ha	j	err j	H	err H	K	err K
1	-	-	-	-	-	10 13 09.25	-58 01 58.10	13.061	0.002	15.008	0.001	13.643	0.001	12.861	13.044	0.001	0.001	11.696	0.021	11.255	0.022	10.837	0.021
52	-	-	-	-	-	10 14 40.36	-57 24 26.24	16.937	0.006	15.457	0.001	12.959	0.001	11.468	12.345	0.001	0.001	8.693	0.024	7.870	0.036	7.414	0.027
89	-	-	-	-	-	10 15 24.77	-57 44 09.28	20.081	0.101	17.776	0.025	18.265	0.016	17.376	17.914	0.022	0.019	15.900	0.089	15.331	0.094	14.970	0.121
162	-	-	-	-	-	10 16 31.33	-57 48 18.68	19.199	0.034	18.923	0.010	17.323	0.006	16.565	17.992	0.017	0.007	15.246	0.054	14.763	0.079	14.509	0.096
164	-	-	-	-	-	10 16 31.97	-57 56 02.37	19.675	0.009	19.702	0.026	17.937	0.014	17.316	16.223	0.008	0.019	15.476	0.064	14.578	0.062	14.519	0.090
175	-	-	-	-	-	10 16 42.53	-57 32 47.65	17.559	0.009	16.168	0.002	13.576	0.001	12.016	13.053	0.001	0.001	9.327	0.026	8.474	0.049	7.953	0.027
413	-	-	-	-	-	10 19 47.82	-57 50 38.64	17.677	0.014	17.057	0.004	15.127	0.002	13.894	14.697	0.003	0.001	11.830	0.026	11.179	0.023	10.872	0.027
496	-	-	-	-	-	10 21 20.56	-57 43 09.40	15.521	0.003	15.231	0.001	13.666	0.001	12.692	13.384	0.001	0.001	11.014	0.023	10.524	0.022	10.292	0.021
578	-	-	-	-	-	10 22 19.90	-57 46 11.21	17.855	0.011	16.506	0.002	14.037	0.001	12.592	13.513	0.001	0.001	9.870	0.024	9.100	0.024	8.600	0.021
601	-	-	-	-	-	10 22 35.02	-58 33 37.82	16.554	0.005	16.692	0.002	15.716	0.002	15.153	15.471	0.004	0.002	14.220	0.056	13.883	0.066	13.810	0.064
677	182	178	112	-	C1* Westerlund 2 MSP 182	10 23 56.18	-57 45 30.00	15.587	0.004	15.349	0.002	13.624	0.001	12.613	13.211	0.001	0.001	10.520	0.015	10.050	0.008	9.750	0.020
712	157	584	-	-	2MASS J10240073-5745253	10 24 00.76	-57 45 25.65	15.376	0.004	15.137	0.002	13.450	0.001	12.437	13.044	0.001	0.001	11.660	0.038	11.150	0.027	10.790	0.031
724	263	722	202	-	C1* Westerlund 2 MSP 263	10 24 01.52	-57 45 57.00	16.696	0.008	16.094	0.003	14.055	0.001	12.885	13.633	0.002	0.001	10.520	0.025	9.910	0.035	9.530	0.036
732	167	804	217	-	C1* Westerlund 2 MSP 167	10 24 02.04	-57 45 27.94	15.858	0.005	15.398	0.002	13.430	0.001	12.306	13.007	0.001	0.001	9.960	0.122	9.357	0.158	8.982	0.095
737	203/444	857	224	-	C1* Westerlund 2 NRM 4	10 24 02.29	-57 45 35.26	14.604	0.003	14.310	0.001	12.566	0.001	11.560	12.170	0.001	0.001	9.450	0.063	8.950	0.090	8.520	0.050
763	171	1039	298	-	C1* Westerlund 2 MSP 171	10 24 04.90	-57 45 28.35	13.886	0.005	15.470	0.002	13.616	0.001	12.552	13.206	0.001	0.001	10.480	0.018	10.000	0.039	9.740	0.033
770	383	-	314	-	C1* Westerlund 2 NRM 3	10 24 06.64	-57 47 15.88	18.263	0.023	17.608	0.006	15.502	0.003	14.248	14.952	0.003	0.002	11.736	0.028	11.008	0.025	10.536	0.023
789	-	-	388	-	C1* Westerlund 2 NRM 2	10 24 16.25	-57 43 43.75	16.495	0.007	15.936	0.003	13.883	0.001	12.664	13.432	0.001	0.001	10.316	0.023	9.624	0.023	9.236	0.021
797	-	-	405	-	C1* Westerlund 2 NRM 1	10 24 21.29	-57 47 27.53	16.048	0.006	15.703	0.002	13.796	0.001	12.636	13.367	0.001	0.001	10.435	0.024	9.745	0.022	9.386	0.019
822	-	-	447	-	2MASS J10243919-5745211	10 24 39.20	-57 45 21.20	16.519	0.007	16.033	0.003	14.084	0.001	12.919	13.644	0.002	0.001	10.709	0.026	10.060	0.027	9.679	0.023

Table 6: Sample table containing the derived parameters of all 1073 objects. The 16th, 50th and 84th percentiles are given for each parameter as well as the χ^2 value at the 50th percentile. The notes column indicates if the object shows emission (EM), is a sub-luminous candidate (SUB), is a blue supergiant candidate (BSG) or is a new O star candidate near Wd 2 (WD2) with similar reddening. The full table can be found in the electronic version of this paper.

ID	$\log(T_{\text{eff}})$ P16 th	$\log(T_{\text{eff}})$ P50 th	$\log(T_{\text{eff}})$ P84 th	A0 P16 th	A0 P50 th	A0 P84 th	u	err u	g	err g	r	err r	i	err i	Ha	err Ha	j	err j	H	err H	K	err K	Notes
1	4.39	4.44	4.39	4.54	4.62	4.54	13.061	0.002	15.008	0.001	13.643	0.001	12.861	13.044	0.001	0.001	11.696	0.021	11.255	0.022	10.837	0.021	EM
52	4.31	4.36	4.31	8.29	8.38	8.29	16.937	0.006	15.457	0.001	12.959	0.001	11.468	12.345	0.001	0.001	8.693	0.024	7.870	0.036	7.414	0.027	BSG
89	4.33	4.43	4.33	5.09	5.26	5.09	20.081	0.101	17.776	0.025	18.265	0.016	17.376	17.914	0.022	0.019	15.900	0.089	15.331	0.094	14.970	0.121	SUB
162	4.40	4.47	4.40	4.69	4.80	4.69	19.199	0.034	18.923	0.010	17.323	0.006	16.565	17.992	0.017	0.007	15.246	0.054	14.763	0.079	14.509	0.096	SUB
164	4.46	4.54	4.46	5.64	5.73	5.64	19.675	0.009	19.702	0.026	17.937	0.014	17.316	16.223	0.008	0.019	15.476	0.064	14.578	0.062	14.519	0.090	EM
175	4.37	4.43	4.37	8.48	8.59	8.48	17.559	0.009	16.168	0.002	13.576	0.001	12.016	13.053	0.001	0.001	9.327	0.026	8.474	0.049	7.953	0.027	BSG
413	4.52	4.61	4.52	6.77	6.83	6.77	17.677	0.014	17.057	0.004	15.127	0.002	13.894	14.697	0.003	0.001	11.830	0.026	11.179	0.023	10.872	0.027	WD2
496	4.46	4.54	4.46	5.53	5.62	5.53	15.521	0.003	15.231	0.001	13.666	0.001	12.692	13.384	0.001	0.001	11.014	0.023	10.524	0.022	10.292	0.021	-
578	4.32	4.37	4.32	8.12	8.22	8.12	17.855	0.011	16.506	0.002	14.037	0.001	12.592	13.513	0.001	0.001	9.870	0.024	9.100	0.024	8.600	0.021	BSG
601	4.32	4.36	4.32	3.35	3.45	3.35	16.554	0.005	16.692	0.002	15.716	0.002	15.153	15.471	0.004	0.002	14.220	0.056	13.883	0.066	13.810	0.064	BSG
677	4.56	4.63	4.56	6.31	6.35	6.31	15.587	0.004	15.349	0.002	13.624	0.001	12.613	13.211	0.001	0.001	10.520	0.015	10.050	0.008	9.750	0.020	SUB
712	4.61	4.66	4.61	4.56	4.60	4.56	15.376	0.004	15.137	0.002	13.450	0.001	12.437	13.044	0.001	0.001	11.660	0.038	11.150	0.027	10.790	0.031	-
724	4.53	4.61	4.53	7.19	7.25	7.19	16.696	0.008	16.094	0.003	14.055	0.001	12.885	13.633	0.002	0.001	10.520	0.025	9.910	0.035	9.530	0.036	-
732	4.52	4.60	4.52	7.03	7.14	7.03	15.858	0.005	15.398	0.002	13.430	0.001	12.306	13.007	0.001	0.001	9.960	0.122	9.357	0.158	8.982	0.095	-
737	4.48	4.56	4.48	6.43	6.51	6.43	14.604	0.003	14.310	0.001	12.566	0.001	11.560	12.170	0.001	0.001	9.450	0.063	8.950	0.090	8.520	0.050	-
763	4.55	4.62	4.55	6.39	6.44	6.39	13.886	0.005	15.470	0.002	13.616	0.001	12.552	13.206	0.001	0.001	10.480	0.018	10.000	0.039	9.740	0.033	-
770	4.50	4.58	4.50	7.68	7.75	7.68	17.559	0.009	16.168	0.002	13.576	0.001	12.016	13.053	0.001	0.001	9.327	0.026	8.474	0.049	7.953	0.027	-
789	4.55	4.62	4.55	7.33	7.38	7.33	15.521	0.003	15.231	0.001	13.666	0.001	12.692	13.384	0.001	0.001	11.014	0.023	10.524	0.022	10.292	0.021	-
797	4.58	4.64	4.58	7.00	7.04	7.00	16.048	0.006	15.703	0.002	13.796	0.001	12.636	13.367	0.001	0.001	10.435	0.024	9.745	0.022	9.386	0.019	-
822	4.54	4.61	4.54	6.98	7.03	6.98	16.519	0.007	16.033	0.003	14.084	0.001	12.919	13.644	0.002	0.001	10.709	0.026	10.060	0.027	9.679	0.023	-

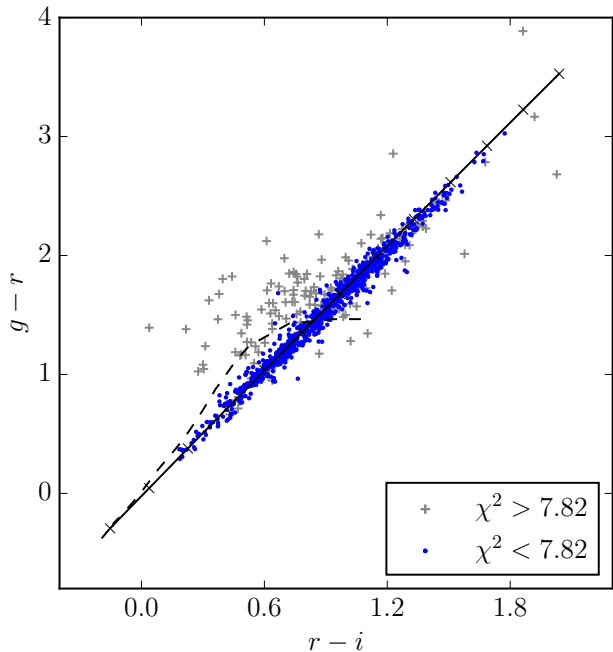


Figure 11. Positions of objects with $\chi^2 \leq 7.82$ (blue dots) and $\chi^2 > 7.82$ (grey crosses) in the $(r - i, g - r)$ plane. The solid black line is the reddening vector of an O9V with $R_V = 3.8$. The dashed line is the unreddened main sequence. We find that a large number of objects with ‘poor’ fits fall away from the OB star reddening vector. These objects show colours that are consistent with eclipsing W UMa contact binaries.

revealed that high χ^2 may be linked to extreme objects like WR stars (6 examples) and carbon stars (1 only). Another rare contaminant may be white dwarf/M dwarf binaries that can present blue $u - g$, alongside red $r - i$. The blue white-dwarf light begins to be overwhelmed by the red dwarf’s light with increasing wavelength, shifting the combined colours below and to the right of the OB reddening track in the $(g - r, r - i)$ diagram (fig 11). Such objects are known to co-locate with reddened OB stars in the $(u - g, g - r)$ diagram or they may fall beyond the RJ reddening vector (Smolčić et al. 2004).

5.2 Parameters of the candidate OB stars

Figure 12 shows the distribution of stellar parameters across the entire selection for the objects fitting successfully to a reddened OB-star SED ($\chi^2 \leq 7.82$ and $\log(T_{\text{eff}}) \geq 4.3$). Coloured in red are the results for all objects within an 8 arcmin box centred on Wd 2 (drawn in Figure 17). It can be seen that those objects in or near the cluster are reported to have similar extinction in the range $5.5 \leq A_0 \leq 7$ (top right panel in Figure 12). Otherwise, the reddenings range more broadly across the full 2 square degrees from $A_0 \simeq 3$ up to $A_0 \simeq 8$. Other features of this particular sight-line are that larger than standard R_V is favoured – a roughly normal distribution in R_V about a mean value of $R_V = 3.84 \pm 0.25$ is obtained – and that most of the selected stars are attributed distances of between ~ 2 kpc ($\mu \simeq 11$) and ~ 6 kpc ($\mu \simeq 14$). The objects in/near Wd2 tend toward the higher end of the

distance modulus range and show a fairly wide spread in extinction law with $3.5 \leq R_V \leq 4.5$.

Echoing the initial mass function (IMF), the distribution in median $\log(T_{\text{eff}})$ values is heavily skewed towards the lower end. The turn over in the $\log(T_{\text{eff}})$ distribution at just below $\log(T_{\text{eff}}) = 4.3$ further supports the conclusion that our initial selection of VPHAS+ sources in the $(u - g, g - r)$ diagram is essentially complete in the desired O to B2 effective temperature range (given our magnitude limits). The coolest object in the candidate list is ~ 16000 K.

Stars with median estimated effective temperatures in excess of 30000K ($\log(T_{\text{eff}}) \geq 4.477$) are regarded as candidate O stars. Of the new discoveries 74 meet this criterion. We can further subdivide this group to distinguish the highly probable O stars: 28 objects have a 16th percentile $\log(T_{\text{eff}})$ exceeding 4.477. Seven of these may be sdO stars (see section 5.3).

Predictably, many of the hottest candidates are in and around Wd 2: this young massive cluster does indeed stand out in this part of the Galactic Plane. Moreover the top left panel in 12 suggests a relative lack of cooler OB stars within the 8 arcmin box centred on the cluster. This could be taken to imply that the stellar mass function of Wd 2 and environs is top heavy. At the same time, there are biases that can favour the detection of more massive stars at the likely distance of the cluster ($\mu \sim 13 - 14$) – namely, the effects of crowding (less massive fainter stars are more likely to be lost in blends) and of magnitude limited selection. However this is unlikely to be all of the explanation given that there are plenty of examples of $A_0 \sim 5.5 - 7$ cool candidates with a similar estimated distance modulus.

Figure 13 shows the upper and lower uncertainties on each parameter as a function of g -band magnitude for all $\chi^2 < 7.82$ objects. The uncertainty on $\log(T_{\text{eff}})$ and A_0 increases for fainter objects, tracking the increase with rising magnitude of the photometric errors. Conversely the uncertainty on R_V shows a slight increase with decreasing magnitude at the bright end. R_V is more difficult to determine for bright objects as they tend to be less obscured. Nevertheless it is evident that both R_V and A_0 are consistently well determined across the entire magnitude range. Our OnIR SED fits deliver A_0 to within $\lesssim 0.09$ mag up to 18th magnitude, rising up to $\lesssim 0.25$ mag at 20th magnitude. We find the median uncertainty on R_V to be 0.081.

5.3 Inferences from the best-fit parameters and other aspects of the photometry

A richer understanding of the candidate objects can be obtained from a combination of more scrutiny of the fit parameters obtained and from a fuller utilisation of the VPHAS+ photometry at our disposal. So far the focus has been on the information to be extracted from the individual OnIR SEDs – treating all candidates as if they are well described as reddened, single, main-sequence OB stars. We can learn more through consideration of the ensemble of objects, and if use is made of the narrowband H α band to separate out emission line stars.

First we acknowledge and relax the main sequence assumption applied so far. The first two panels of Figure 14 show scatter plots of the best-fit median distance modulus, μ , vs. $\log(T_{\text{eff}})$ and vs. A_0 for the candidate OB stars. Differ-

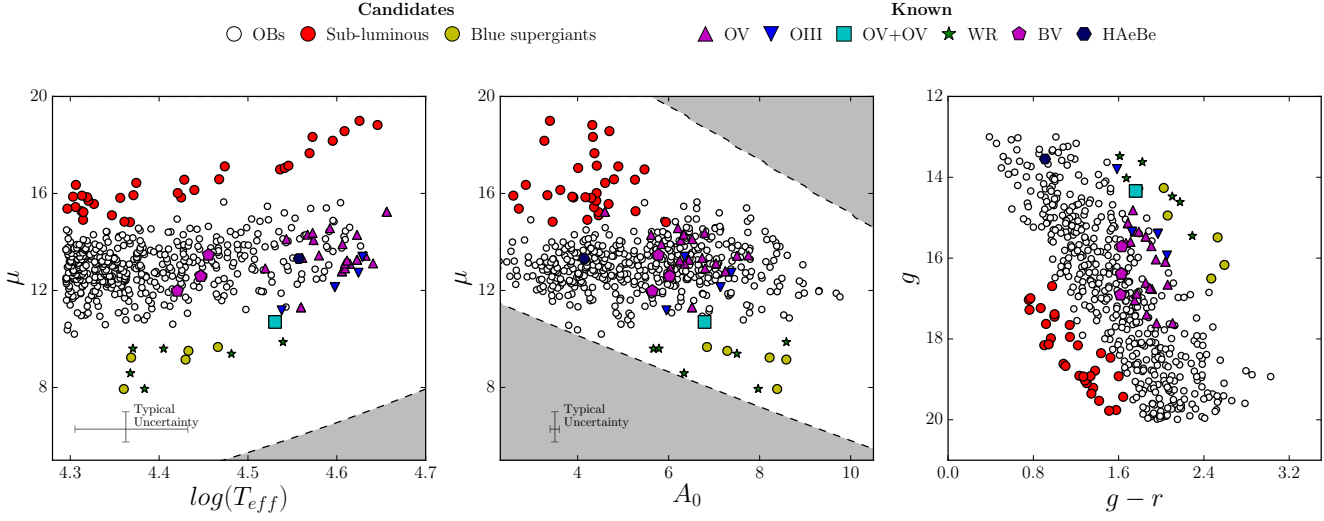


Figure 14. 2-D distribution of the best fit parameters for the final selection of OB candidates ($\chi^2 \leq 7.82$ and $\log(T_{\text{eff}}) \geq 4.3$) and objects in the selection with known spectral type (the carbon star lays outside the range of 2 of these diagrams and was therefore not included). Objects shown in red and yellow are thought to be candidate sub-luminous OB stars and candidate blue supergiants respectively. The areas shaded in grey are where we cannot detect OB stars given the survey limits.

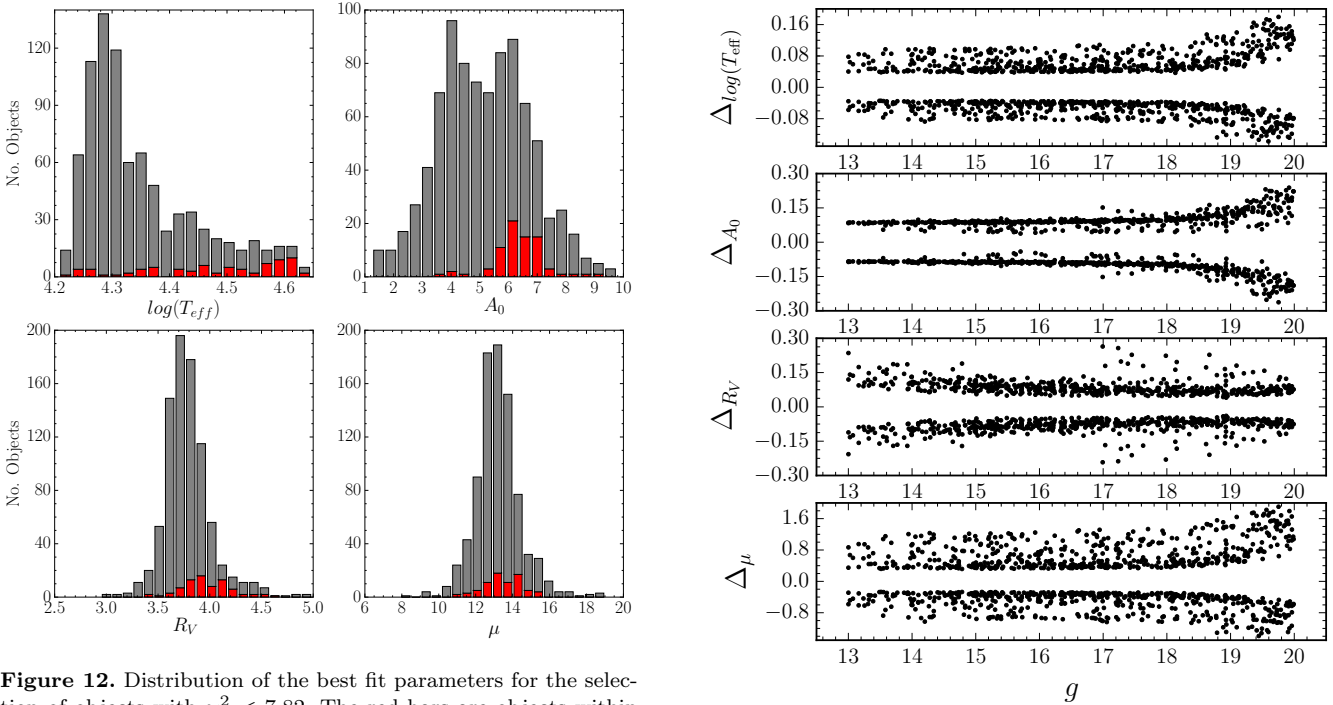


Figure 12. Distribution of the best fit parameters for the selection of objects with $\chi^2 < 7.82$. The red bars are objects within and 8 arcmin box of Wd 2 while the grey bars are the wider selection. We find that the objects spatially associated with Wd 2 show a tight distribution in A_0 and provide an over density of objects in the $5.5 \leq A_0 \leq 7$ range and also show a wider spread in R_V .

ent symbols are over-plotted to pick out the already known objects listed in SIMBAD as well as the O stars of Vargas Álvarez et al. (2013). The areas shaded in grey are where we cannot detect OB stars given the survey limits. The objects plotted as red circles have relatively low extinction but, if

we take the returned distance moduli at face value, they would have to be construed as very distant (> 10 kpc) when compared to the known OB stars. It is more plausible that these are intrinsically sub-luminous objects rather than distant OB stars located in remarkably clear reddening holes.

Their scattered spatial distribution across the whole field shown in Figure 17 supports this argument.

The converse argument can be applied to those objects plotted as yellow circles: they are found to have more than 6 magnitudes of extinction but are seemingly very close (less than ~ 700 pc away, $\mu < 9$). We suspect that these objects are intrinsically much higher-luminosity, evolved B stars. The proximity of these stars in the figures to the (poorly-fit) known WR stars, including the highly-luminous WR20a, lends credibility to this interpretation.

Referring back to the photometry in the form of a $(g, g - r)$ colour magnitude diagram (CMD), these interpretations are seen to make sense – the sub-luminous and over-luminous objects form tracks separated from the main-sequence – see the third panel of Figure 14. Table 7 lists these extreme objects. There will be further discussion of them in Section 6. The main concentration of objects appears in the $11.5 < \mu < 14$ mag range which equates to distances ranging from 2 – 6kpc. This encloses the derived distance range of the Carina arm traced in CO by Grabelsky et al. (1988), near its tangent.

We can also use the VPHAS+ $H\alpha$ measurements to uncover any emission line stars in our selection. The presence of emission lines implies the presence of ionized circumstellar gas which, among massive OB stars, most commonly indicates classical Be stars with circumstellar disks. Although the OnIR SEDs of classical Be stars are not greatly different from normal B stars of similar effective temperature, the derived interstellar extinctions from SED fits that do not take into account the circumstellar continuum emission will nevertheless be overestimated. We have used the $(r - i, r - H\alpha)$ diagram to select all objects that lie more than 0.1 mag in $r - H\alpha$ above the O9V reddening vector (this equates to $\sim 10\text{\AA}$ in emission line equivalent width). Figure 15 shows this selection. Using the relation between $EW(H\alpha)$ and added colour excess $E(B - V)$ due to the presence of a circumstellar disk in classical Be stars from Dachs et al. (1988), we can estimate that the derived reddenings (A_0) for our $H\alpha$ -excess stars will have been inflated by between ~ 0.1 and ~ 0.3 magnitudes. There are 17 of these objects in the $\chi^2 \leq 7.82$ and $\log(T_{\text{eff}}) \geq 4.3$ group and a further 63 with $\chi^2 > 7.82$ and/or $\log(T_{\text{eff}}) < 4.3$. Objects with $H\alpha$ excess are marked in Table 6.

5.4 Reddening

After removing the obvious sub/over-luminous objects and the emission line stars from the selection we are left with a cleaner selection of 458 \sim non-emission OB candidates and 19 known OB stars available for further examination of their reddening properties.

Given our tight grasp on A_0 and R_V , it is of interest to consider their interdependence. R_V is plotted as a function of A_0 in Figure 16. The left panel of this Figure includes those objects within an 8 arcmin box around Wd 2 and the right hand panel excludes them. The areas shaded in grey are where we cannot detect OB stars given the survey limits. In both cases we can see a moderate positive correlation in R_V as a function of A_0 (correlation coefficient $r = 0.47$ and $r = 0.45$ respectively). On comparing the two panels, it is evident that the members of Wd 2 drive up the R_V trend more sharply when they are included. The shaded

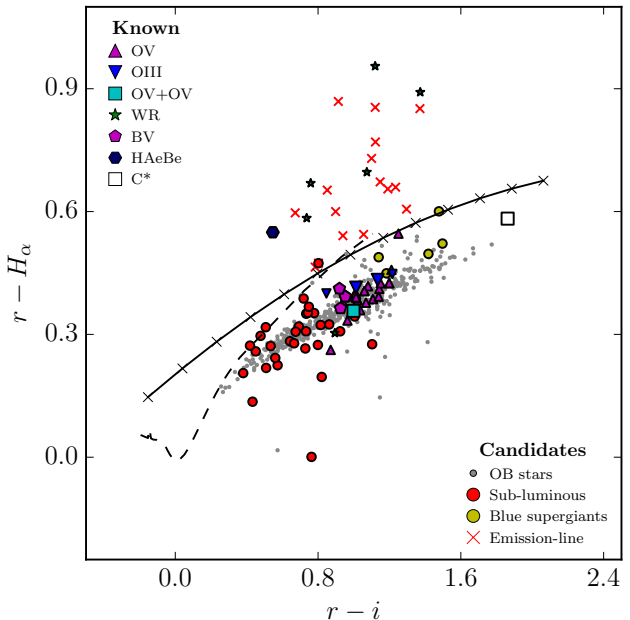


Figure 15. 13 of the $\chi^2 \leq 7.82$ and $\log(T_{\text{eff}}) \geq 4.3$ objects show $H\alpha$ excess. As emission is usually associated with circumstellar dust; the derived extinction may be incorrect. The solid line is the reddening vector of an O9V raised by 0.1 in $r - H\alpha$.

background shows that the trends seen are independent of the boundaries set by the survey selection limits. Given that it was demonstrated in Section 4.2 that the fitting method generates negligible covariance between A_0 and R_V , we can say with confidence that the correlation apparent now is related to the physical nature of the volume of space under study.

It is commonly accepted that increasing R_V is linked to increasing typical dust grain size, and that values of 3.5 and more are associated with denser molecular cloud environments (see e.g. Draine 2003). The ~ 2 square degrees under examination here sample sight-lines lying just inside the Carina Arm tangent direction. Our pencil beam is evidently one that would initially pass through the atomic diffuse interstellar medium and then enter the dense clouds of the Carina Arm, wherein Wd 2 is located. In this situation it makes sense that as the dust column grows it becomes ever more dominated by the dense/molecular ISM component – i.e. R_V tends to rise. However the rise is not dramatic, and the data points show significant dispersion, which may imply that the variation in the dust properties within the sampled volume is not especially coherent. The effect of the bright limit of the survey is to remove sensitivity to A_0 much below 2–3, or to distances less than ~ 3 kpc (see below). Current maps of Galactic spiral arm structure place this distance already within the Carina Arm (Russell 2003; Vallée 2014).

The clear message of Figure 16 is that the typical, if necessarily idealised, reddening law for this sight-line is $R_V \sim 3.8$, which rises much less sharply with decreasing wavelength than the Galactic average of $R_V = 3.1$ (see Figure 13 in Fitzpatrick & Massa 2007).

Table 7. Table containing the derived stellar parameters of the sub-luminous and blue supergiant candidates in the $\chi^2 \leq 7.82$ and $\log(T_{\text{eff}}) \geq 4.3$ group.

ID	RA	DEC	g	$\log(T_{\text{eff}})$	A_0	R_V	μ	χ^2
Sub-Luminous								
19	10 13 40.87	-57 43 15.38	18.13	$4.65^{+0.04}_{-0.05}$	$4.32^{+0.09}_{-0.09}$	$4.95^{+0.16}_{-0.15}$	$18.82^{+0.50}_{-0.69}$	7.09
28	10 13 54.74	-58 14 33.73	18.91	$4.31^{+0.05}_{-0.04}$	$4.36^{+0.13}_{-0.13}$	$3.82^{+0.17}_{-0.16}$	$15.44^{+0.45}_{-0.37}$	3.53
82	10 15 21.46	-57 53 30.64	19.43	$4.37^{+0.08}_{-0.06}$	$5.94^{+0.13}_{-0.13}$	$4.03^{+0.10}_{-0.10}$	$14.82^{+0.77}_{-0.52}$	1.11
86	10 15 22.76	-57 48 21.73	18.67	$4.57^{+0.08}_{-0.08}$	$4.34^{+0.16}_{-0.17}$	$4.17^{+0.23}_{-0.21}$	$18.33^{+0.98}_{-0.99}$	2.10
89	10 15 24.77	-57 44 09.28	19.78	$4.43^{+0.13}_{-0.09}$	$5.26^{+0.15}_{-0.17}$	$3.79^{+0.13}_{-0.12}$	$16.57^{+1.47}_{-0.88}$	1.97
96	10 15 36.78	-57 46 58.03	17.65	$4.37^{+0.05}_{-0.05}$	$3.34^{+0.10}_{-0.10}$	$3.13^{+0.11}_{-0.10}$	$15.93^{+0.53}_{-0.42}$	0.82
153	10 16 25.54	-58 33 18.54	18.93	$4.61^{+0.06}_{-0.08}$	$4.70^{+0.09}_{-0.09}$	$3.84^{+0.11}_{-0.11}$	$18.57^{+0.83}_{-0.99}$	6.51
162	10 16 31.33	-57 48 18.68	18.92	$4.47^{+0.09}_{-0.07}$	$4.80^{+0.10}_{-0.11}$	$3.35^{+0.09}_{-0.09}$	$16.58^{+1.04}_{-0.69}$	5.05
177	10 16 44.32	-58 01 29.97	19.02	$4.32^{+0.06}_{-0.05}$	$4.17^{+0.13}_{-0.13}$	$3.60^{+0.14}_{-0.13}$	$15.84^{+0.54}_{-0.42}$	2.71
202	10 17 01.28	-58 05 29.31	19.35	$4.47^{+0.11}_{-0.08}$	$4.89^{+0.13}_{-0.14}$	$3.87^{+0.15}_{-0.14}$	$17.11^{+1.34}_{-0.86}$	3.96
219	10 17 15.78	-57 23 13.80	19.53	$4.37^{+0.07}_{-0.06}$	$4.60^{+0.15}_{-0.15}$	$3.57^{+0.16}_{-0.15}$	$16.43^{+0.75}_{-0.54}$	1.31
274	10 17 59.10	-58 01 05.92	18.16	$4.31^{+0.05}_{-0.04}$	$2.86^{+0.13}_{-0.13}$	$3.27^{+0.20}_{-0.18}$	$16.35^{+0.43}_{-0.36}$	3.30
275	10 17 59.67	-57 48 12.93	17.03	$4.30^{+0.04}_{-0.04}$	$2.71^{+0.10}_{-0.10}$	$3.61^{+0.18}_{-0.17}$	$15.37^{+0.35}_{-0.30}$	1.17
292	10 18 11.80	-58 20 12.24	19.21	$4.33^{+0.05}_{-0.05}$	$4.68^{+0.13}_{-0.13}$	$3.82^{+0.15}_{-0.14}$	$15.57^{+0.50}_{-0.41}$	1.62
402	10 19 39.37	-58 29 18.43	19.76	$4.31^{+0.07}_{-0.06}$	$5.27^{+0.15}_{-0.15}$	$3.72^{+0.12}_{-0.11}$	$15.27^{+0.64}_{-0.47}$	3.79
468	10 20 48.03	-57 45 45.52	18.35	$4.35^{+0.05}_{-0.05}$	$4.46^{+0.12}_{-0.12}$	$3.47^{+0.12}_{-0.12}$	$15.10^{+0.51}_{-0.41}$	0.35
472	10 20 53.73	-57 58 41.78	17.95	$4.55^{+0.10}_{-0.08}$	$4.42^{+0.08}_{-0.09}$	$3.94^{+0.12}_{-0.11}$	$17.14^{+1.22}_{-0.89}$	3.28
474	10 20 54.07	-58 02 32.59	18.92	$4.30^{+0.05}_{-0.04}$	$3.88^{+0.12}_{-0.12}$	$3.40^{+0.14}_{-0.13}$	$15.87^{+0.42}_{-0.35}$	6.59
484	10 21 07.91	-57 33 52.74	18.16	$4.57^{+0.09}_{-0.08}$	$4.37^{+0.08}_{-0.09}$	$3.70^{+0.11}_{-0.10}$	$17.66^{+1.09}_{-0.95}$	3.39
486	10 21 10.28	-58 10 46.02	18.62	$4.36^{+0.05}_{-0.05}$	$4.30^{+0.11}_{-0.11}$	$4.33^{+0.17}_{-0.16}$	$15.82^{+0.50}_{-0.43}$	1.42
601	10 22 35.02	-58 33 37.82	16.69	$4.36^{+0.05}_{-0.04}$	$3.45^{+0.10}_{-0.10}$	$3.69^{+0.13}_{-0.13}$	$14.83^{+0.46}_{-0.38}$	0.97
647	10 23 27.84	-57 54 56.79	19.03	$4.54^{+0.11}_{-0.09}$	$5.47^{+0.09}_{-0.10}$	$4.39^{+0.13}_{-0.12}$	$16.99^{+1.38}_{-1.04}$	5.40
810	10 24 31.14	-57 33 45.22	16.99	$4.60^{+0.07}_{-0.08}$	$3.27^{+0.15}_{-0.15}$	$4.03^{+0.26}_{-0.24}$	$18.17^{+0.94}_{-1.01}$	1.71
819	10 24 36.96	-58 22 47.18	17.28	$4.31^{+0.04}_{-0.04}$	$2.59^{+0.11}_{-0.11}$	$3.51^{+0.20}_{-0.18}$	$15.91^{+0.39}_{-0.33}$	5.83
842	10 24 58.98	-57 59 56.24	17.45	$4.42^{+0.07}_{-0.05}$	$3.91^{+0.14}_{-0.14}$	$4.11^{+0.23}_{-0.21}$	$15.83^{+0.77}_{-0.57}$	0.66
870	10 25 25.08	-57 59 04.50	17.98	$4.31^{+0.04}_{-0.04}$	$4.21^{+0.12}_{-0.12}$	$4.99^{+0.22}_{-0.23}$	$14.91^{+0.42}_{-0.33}$	0.71
894	10 25 47.01	-57 46 51.19	19.09	$4.32^{+0.06}_{-0.05}$	$4.41^{+0.15}_{-0.15}$	$3.84^{+0.18}_{-0.17}$	$15.70^{+0.54}_{-0.43}$	1.49
956	10 26 57.82	-57 36 16.66	17.39	$4.54^{+0.09}_{-0.08}$	$4.01^{+0.10}_{-0.10}$	$4.44^{+0.19}_{-0.17}$	$17.05^{+1.11}_{-0.88}$	7.77
989	10 27 34.13	-57 36 25.34	18.79	$4.31^{+0.05}_{-0.04}$	$4.46^{+0.13}_{-0.13}$	$3.59^{+0.14}_{-0.13}$	$15.23^{+0.46}_{-0.39}$	3.04
1024	10 28 14.60	-57 41 36.33	17.24	$4.44^{+0.07}_{-0.06}$	$3.62^{+0.14}_{-0.14}$	$4.22^{+0.26}_{-0.24}$	$16.14^{+0.82}_{-0.61}$	1.70
1052	10 28 50.85	-57 45 56.73	17.63	$4.63^{+0.05}_{-0.06}$	$3.39^{+0.12}_{-0.12}$	$3.80^{+0.18}_{-0.17}$	$18.99^{+0.61}_{-0.81}$	2.77
1059	10 28 56.00	-58 09 02.55	18.46	$4.42^{+0.07}_{-0.05}$	$4.42^{+0.10}_{-0.10}$	$3.27^{+0.09}_{-0.09}$	$16.02^{+0.72}_{-0.53}$	5.96
Blue supergiants								
52	10 14 40.36	-57 24 26.24	15.49	$4.36^{+0.05}_{-0.05}$	$8.38^{+0.10}_{-0.10}$	$3.77^{+0.05}_{-0.05}$	$7.93^{+0.51}_{-0.40}$	2.28
175	10 16 42.53	-57 32 47.65	16.17	$4.43^{+0.08}_{-0.06}$	$8.59^{+0.10}_{-0.10}$	$3.77^{+0.05}_{-0.05}$	$9.15^{+0.82}_{-0.56}$	1.04
188	10 16 53.91	-57 55 02.11	14.26	$4.47^{+0.09}_{-0.06}$	$6.84^{+0.09}_{-0.09}$	$3.81^{+0.06}_{-0.06}$	$9.67^{+0.99}_{-0.63}$	0.25
452	10 20 31.60	-58 03 08.72	14.95	$4.43^{+0.07}_{-0.05}$	$7.29^{+0.09}_{-0.10}$	$4.03^{+0.07}_{-0.07}$	$9.51^{+0.77}_{-0.53}$	0.91
578	10 22 19.90	-57 46 11.21	16.51	$4.37^{+0.06}_{-0.05}$	$8.22^{+0.10}_{-0.10}$	$3.80^{+0.05}_{-0.05}$	$9.23^{+0.54}_{-0.41}$	2.32

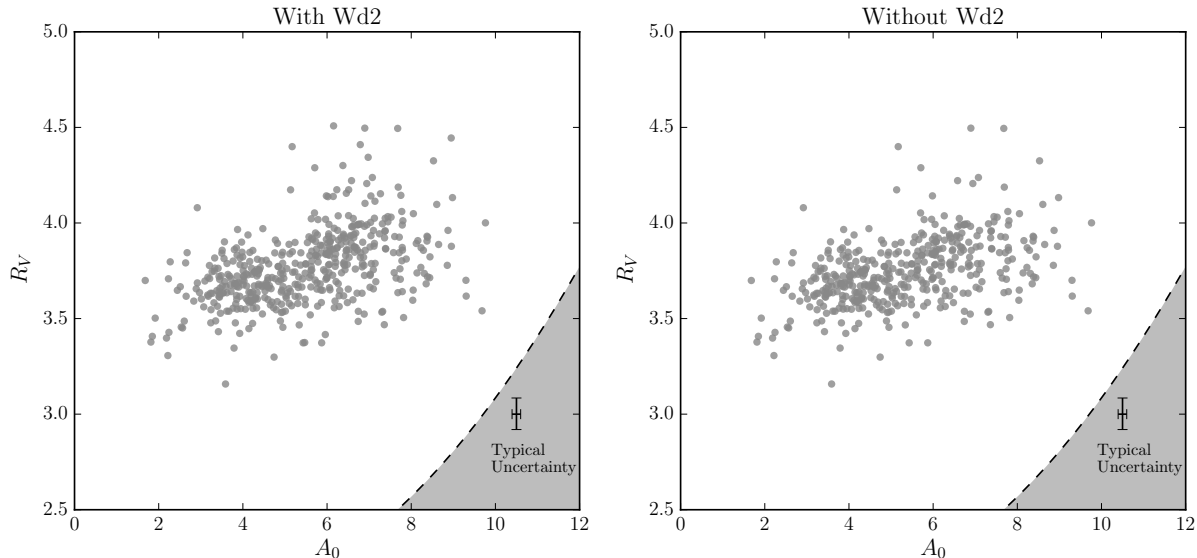


Figure 16. A_0 vs. R_V plot for the final selection with and without the objects within the 8 arcmin box surrounding Wd 2. There is a modest increase in R_V as a function of A_0 in either case with correlation coefficient $r = 0.47$ and $r = 0.45$ respectively. The areas shaded in grey are where we cannot detect OB stars given the survey limits.

6 DISCUSSION

6.1 The number and spatial distribution of the OB candidates

Figure 17 shows the location of each new candidate in the 2 square degrees for which the SED fit returned $\chi^2 \leq 7.82$ and $\log(T_{\text{eff}}) \geq 4.3$, over-plotted on the VPHAS+ H α mosaic. Each star is colour-coded according to its derived extinction, A_0 . The 527 objects are scattered across the field, with lower reddenings ($A_0 < 5$) dominating in the southern half. Apart from in Westerlund 2 itself, the distribution is sparser and more highly-reddened in the north. Towards the NW and the tangent direction, roughly at RA 10h11m, Dec -56 14 (J2000) (Dame 2007), the most reddened objects ($A_0 > 8$) are found.

489 of the objects shown have not been identified previously as confirmed or candidate OB stars. Previous works by Reed (2003), and by Kaltcheva & Golev (2012) have noted a further 26 stars earlier than B3 within this region – all of which are brighter than $V = 11$, and therefore not in our sample. Also for reasons of brightness, our sample does not include any stars obviously associated with IC 2581. Turner (1978) studied the cluster – home to a number of early B stars – establishing a distance of 2.87 kpc, and a typical reddening corresponding to $A_0 \sim 1.5$. For the present selection, this cluster is too close and too lowly-reddened: a B3 main sequence star with $A_0 = 1.5$ needs to be at a distance of 3.8 kpc to achieve $g = 13$. The one star that has been uncovered close to IC 2581 is a candidate sub-luminous object, likely to be at a much shorter distance and unconnected to IC 2581. It can be seen in Figure 16 that $A_0 = 1.9$ for the least reddened candidate OB star in the sample.

It has been argued before by e.g. Grabelsky et al. (1988) and Dame (2007) that the Carina Arm tangent region traced in CO spans the distance range from 3 to 5 kpc. At larger distances the conical volume captured here reaches beyond

the Solar Circle where declining amounts of molecular gas are detected. Taking note of these considerations, it seems likely that the high values of R_V , trending from 3.6 to 3.9, revealed by our SED fits (Figure 16) are largely a product of the dominant and increasing contribution to the total extinction from the dust column of the Carina Arm. Similarly Povich et al. (2011) found it necessary to adopt $R_V = 4$ for embedded Carina Arm objects at $l \sim 287^\circ$. In contrast, Turner (1978) determined R_V to be 3.11 ± 0.18 across this region, based on bright OB stars with extinctions below A_V of 2 – clearly the foreground to our sample. Indeed it seems likely that much of the extinction of the OB population spanning $A_0 \sim 2$ to $A_0 \sim 9$ accumulates within the Carina Arm. The appearance of Figure 14 indicates few detected main sequence OB stars beyond a distance modulus of 14 (6kpc).

6.2 Westerlund 2

Figures 12 and 16 tell us that a single value of R_V cannot be used to describe the extinction law of sight lines towards all objects in Wd 2. Instead we find that R_V ranges from approximately 3.5 to 4.5 within the cluster. Similar spreads in R_V within star clusters has previously been found by Fitzpatrick & Massa (2007) and highlights the importance of deriving R_V on a star-by-star basis. Hur et al. (2015) describe a hybrid extinction model with $R_V = 3.33 \pm 0.03$ to $A_0 \sim 3$ (based on three stars), while $R_V = 4.14 \pm 0.08$ is required for stars in Wd 2. Figure 16 cautions against this clear-cut interpretation, even while our results are numerically consistent with theirs. Reality is more fractal and it is best not to place too much weight on small numbers of stars.

In Figure 12 we noticed a tight distribution in A_0 for the objects close to Wd 2 as projected on the sky. While there are no new OB star candidates in the central region of

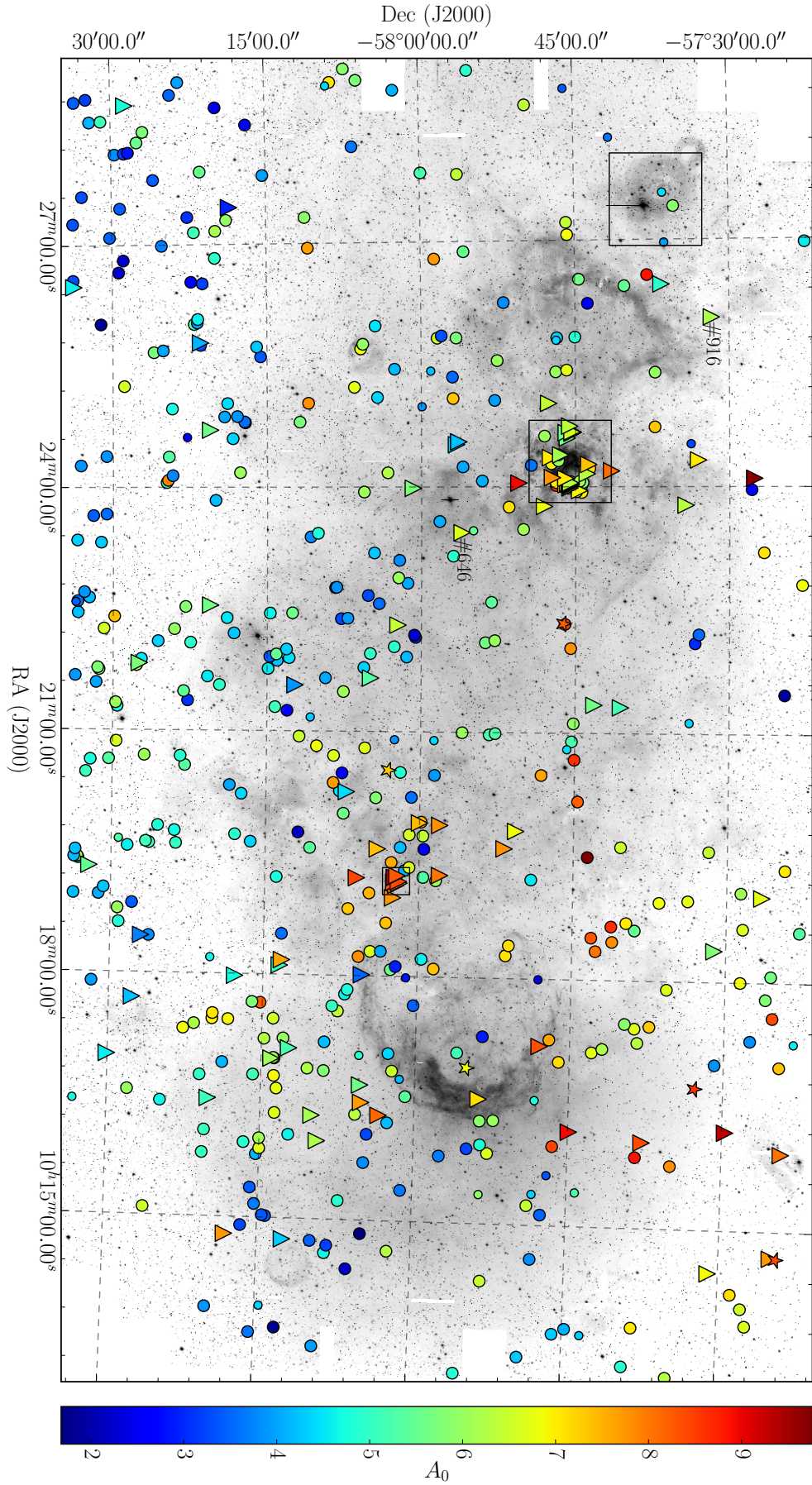


Figure 17: Known and candidate OB stars, in our selection, coloured according to their inferred reddening (A_0) and over-plotted on the high-confidence inverse VPHAS+ H α image. The boxes pick out the known clusters IC 2581, Wd 2, and DBS2003 45 (working from east to west). The symbols used have the following interpretations: \circ stars with $\log(T_{\text{eff}}) > 4.477$ are triangles; early B stars, $4.300 \leq \log(T_{\text{eff}}) \leq 4.477$ are large circles; stars and small circles represent the blue supergiants and under-luminous objects respectively. The white space under the object near the eastern boundary is currently a region of reduced confidence in H α (without inclusion of the adjacent field) Low resolution spectroscopy of object #916 and #646 suggests their spectral types may be early as O3-O4 (Mohr-Smith et al in prep).

Table 8. The reddening parameters and angular separation from the centre of Wd 2 (RA 10 24 18.5 DEC -57 45 32.3 (J2000)) of new O star candidates with similar reddening to the cluster, outside the 8 arcmin box shown in figure 17. All objects have $\log(T_{\text{eff}}) > 4.477$ and $5.8 > A_0 > 7.2$. See Tables 5 and 6 for the full set of data.

ID	g	A_0	Separation (arcmin)
44	16.62	$6.88^{+0.07}_{-0.09}$	80.21
121	14.28	$6.21^{+0.06}_{-0.08}$	70.59
191	17.43	$6.05^{+0.09}_{-0.09}$	64.98
144	16.94	$6.13^{+0.07}_{-0.09}$	68.46
161	19.28	$7.11^{+0.07}_{-0.12}$	62.73
346	16.60	$6.76^{+0.07}_{-0.09}$	46.51
413	17.06	$6.83^{+0.05}_{-0.06}$	36.42
576	15.40	$6.42^{+0.05}_{-0.07}$	23.13
916	15.01	$6.19^{+0.05}_{-0.07}$	19.67
646	15.58	$6.69^{+0.06}_{-0.08}$	12.60
796	16.37	$7.03^{+0.05}_{-0.07}$	12.50
662	15.33	$6.30^{+0.05}_{-0.06}$	12.06
846	16.82	$6.39^{+0.04}_{-0.05}$	6.03
661	17.21	$6.81^{+0.04}_{-0.05}$	5.05

Wd 2 (within the 8 arcmin box shown in fig 17), there are a handful of probable O stars scattered across the field that share its extinction. All objects that have extinctions consistent to within 1σ of the mean of known objects in Wd 2 ($5.8 > A_0 > 7.2$) and have $\log(T_{\text{eff}}) > 4.477$ are identified in Table 8. It is possible that these have been ejected from Wd 2 by dynamical interactions or after supernova explosions in binary systems (Allen & Poveda 1971; Gies & Bolton 1986). Given a derived distance of ~ 5 kpc to Wd 2, an object that is separated from the cluster by ~ 20 arcmin on the sky would have to have travelled a minimum distance of ~ 30 pc in 1–2 Myr. This would equate to a minimum (plane-of-sky) velocity of ~ 25 km/s. Given that massive stars can attain runaway velocities of up to ~ 200 km/s through dynamical encounters between binary systems (Gvaramadze et al. 2010), it is not unreasonable to consider that these objects have been ejected recently from Wd 2. Alternatively these stars may have formed in situ within the wider star forming region on a similar time scale to the cluster. Low resolution spectroscopy of object #916 and #646 suggests their spectral types may be early as O3-O4 (Mohr-Smith et al in prep). Their positions are marked on Figure 17.

As a final point of interest, we note that the more reddened cluster DBS2003 45, picked out in figure 17 as well, also appears to be surrounded by a scatter of OB stars that are reddened similarly to the cluster.

6.3 Candidate blue supergiants and sub-luminous stars

The results from Section 5.3 suggest the presence of 5 high luminosity B stars scattered across the field. If they are early-B supergiants, their absolute visual magnitudes would be in the region of ~ -6.5 (Crowther et al. 2006). On

correcting the previous main-sequence assumption, we find their derived distance moduli, μ , rise from ~ 9 to ~ 13.5 , placing them amongst the general OB population that we pick out. Meylan & Maeder (1983) estimate a surface density of around 10 - 20 blue supergiants (BSGs) per kpc^2 in the Galactic Plane. Assuming that our selection spans distances from 2 - 6 kpc we are sampling a projected disk surface area of a little over 1 kpc^2 ; so finding 5 candidates undershoots the surface density prediction but not to the extent that it can be claimed to be inconsistent with it. Given that these candidates are affected by saturation in the i band ($i \lesssim 12$), there may be one or two BSGs that have fallen into the ‘poor-fit’ group due to saturation in one or more bands.

We also find evidence for the presence of a population of subdwarf stars (see table 7 and figure 14). Of these 9 may be sdO stars, leaving 23 in the sdB category. The absolute magnitudes of the latter range from $M_V = 3 - 6$ (Stark & Wade 2003). Since these objects are ~ 6 mag fainter than their main-sequence counterparts, their distance moduli are likely to be ~ 10 as opposed to the estimated values of ~ 16 . This behaviour and the spatial scattering of the subdwarf candidates suggests that we are looking at a group of moderately reddened $A_0 \sim 4$ stars in the foreground of the main OB population. We are biased to select more highly reddened subdwarf stars due to the 2MASS faint limit as discussed in Section 5.1.2. If this limit was not in place we would expect to find more lowly reddened sdB stars in the selection.

Although the SED-fitting we have performed has no sensitivity to surface gravities and limited sensitivity to stellar effective temperature, the fact that the Carina Arm region studied falls near the tangent has allowed us to pick out the extreme objects purely from their outlying distance moduli – relative to the near MS stars concentrated in the range $11 < \mu < 14$. While this approach works here, it is evident that in other sight-lines, where the population of OB stars may be spread more uniformly across a larger distance range, the luminosity extremes would not stand out in the same way.

7 CONCLUSIONS

In summary, we have demonstrated a method for selecting and parametrizing the reddening and basic stellar properties of OB stars uniformly across large areas of the Southern sky using VPHAS+, and NIR survey data. The selection presented here has resulted in reddening parameters for 848 O and B stars (see table 4). Of these, 489 are well-fit new OB stars hotter than 20000 K, including 74 probable O stars. This has been achieved by reaching down to $g = 20$ mag and approaches a factor of 10 increase relative to the small number of known and candidate O to B2 stars in the region.

By bringing together VPHAS+ u, g, r, i photometry with NIR 2MASS photometry, we are able to determine both the value of the extinction, A_0 , and test and select the most appropriate reddening law, as parametrised by R_V , to a high degree of accuracy: both are typically measured to better than 0.1 (magnitudes in the case of A_0). Pleasingly there are signs that the still preliminary nature of the photometric calibration of the VPHAS+ survey data blends well with the now well-established 2MASS calibration.

We set out expecting to only gain a crude impression of

stellar effective temperatures (and hence distance moduli), and so it has turned out. But we have found a satisfying consistency with earlier results in our benchmark region around the much-studied cluster Westerlund 2, confirming that our methods are sound and able to e.g distinguish early O stars from late-O and early-B stars. This represents an efficient start to selection that needs to be followed up by spectroscopic confirmation and measurement of stellar parameters. With precise spectroscopic parameters in hand, the photometry can be re-used for direct and even more precise measurement of reddening laws.

We have also seen how the high resolution and wide field of view of OmegaCam can bring a wider context to the study of open clusters and OB associations, through an ability to identify potentially-related stars that have either been ejected from clusters or simply have formed – perhaps as part of a wider star-formation event – in relative isolation in the surrounding field. This study has also uncovered 5 BSG candidates as well as 32 reddened candidate subdwarfs of which 9 may be sdO stars.

In the future, we aim to roll out this method to support the complete characterisation of the massive-star population and the patterns of extinction they can reveal across the entire Southern Galactic mid-plane to distances of ~ 5 kpc or more. Garmany et al. (1982) were able to claim a volume-limited census to ~ 2.5 kpc 3 decades ago – now it should be possible to expand the effective volume by a factor of 4 or so, with the difference this time that Gaia parallaxes as they appear will bestow a confidence as to what the volume limits actually are.

ACKNOWLEDGEMENTS

This paper is based on data products from observations made with ESO Telescopes at the La Silla Paranal Observatory under programme ID 177.D-3023, as part of the VST Photometric H Survey of the Southern Galactic Plane and Bulge (VPHAS+, www.vphas.eu). Use is also made of data products from the Two Micron All Sky Survey, 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.

This research made use of Astropy, a community-developed core Python package for Astronomy (Astropy Collaboration et al. 2013) and TopCat (Taylor 2005).

The authors wish to thank the referee for helpful comments that have improved this paper. MM-S acknowledges a studentship funded by the Science and Technology Facilities Council (STFC) of the United Kingdom (ref. ST/K502029/1). JED and GB acknowledge the support of a research grant funded by the STFC (ref. ST/J001333/1). NJW is in receipt of a fellowship funded by the Royal Astronomical Society of the United Kingdom.

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