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Candidate Hα emission and absorption line sources in the Galactic Bulge Survey

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ABSTRACT

We present a catalogue of candidate Hα emission and absorption line sources and blue objects in the Galactic Bulge Survey (GBS) region. We use a point source catalogue of the GBS fields (two strips of \((l \times b) = (6^\circ \times 1^\circ)\) centred at \(b = 1^\circ.5\) above and below the Galactic Centre), covering the magnitude range \(16 \leq r' \leq 22.5\). We utilize \((r' - i', r' - H\alpha)\) colour–colour diagrams to select Hα emission and absorption line candidates, and also identify blue objects (compared to field stars) using the \(r' - i'\) colour index. We identify 1337 Hα emission line candidates and 336 Hα absorption line candidates. These catalogues likely contain a plethora of sources, ranging from active (binary) stars, early-type emission line objects, cataclysmic variables (CVs) and low-mass X-ray binaries (LMXBs) to background active galactic nuclei (AGN). The 389 blue objects we identify are likely systems containing a compact object, such as CVs, planetary nebulae and LMXBs. Hot subluminous dwarfs (sdO/B stars) are also expected to be found as blue outliers. Cross-matching our outliers with the GBS X-ray catalogue yields 16 sources, including 7 (magnetic) CVs and 1 qLMXB candidate among the emission line candidates and 1 background AGN for the absorption line candidates. One of the blue outliers is a high-state AM CVn system. Spectroscopic observations combined with the multiwavelength coverage of this area, including X-ray, ultraviolet and (time-resolved) optical and infrared observations, can be used to further constrain the nature of individual sources.

Key words: binaries: symbiotic – stars: emission line, Be – novae, cataclysmic variables – white dwarfs – Galaxy: bulge – galaxies: active.

1 INTRODUCTION

The presence of an ionizing radiation field can lead to hydrogen emission lines, while the presence of neutral hydrogen can result in absorption features in the optical spectrum of astronomical objects. From the properties of the H Balmer lines, one can infer characteristics of the system under study. For example, the properties of single and/or double-peaked lines can allow us to infer geometrical properties (Horne & Marsh 1986), the presence or absence of an accretion disc (Schwope et al. 2000; Ratti et al. 2012), or the nature of the compact object and/or donor star (Steeghs & Casares 2002; van Spaandonk et al. 2010; Casares 2015, 2016).

Historically, large-scale photometric Hα surveys with modest spatial resolution focused on extended sources of emission to study star-forming regions, galaxy groups and supernova remnants (Davies, Elliott & Meaburn 1976, and references there-in). More recently, higher resolution surveys such as the INT Photometric Hα survey (IPHAS; Drew et al. 2005, Barentsen et al. 2014) have focused on the Galactic plane to uncover and study compact sources of emission, typically associated with various stages of stellar evolution. The most noteworthy Hα survey covering the Galactic bulge is the photographic Anglo–Australian Observatory UK Schmidt Telescope Supercosmos Hα Survey (Parker et al. 2005), going down to...
$R \sim 19.5$ mag in the latitude range $|b| \leq 10^\circ$. Currently ongoing is the VST Photometric H$\alpha$ Survey of the Southern Galactic Plane and Bulge (VPHAS+; Drew et al. 2014) that will cover the Galactic bulge and plane in five filters down to at least 20th magnitude.

The analysis of colour–colour diagrams (CCDs) to search for H$\alpha$ emission line objects has been introduced by the IPHAS collaboration. Witham et al. (2008) present a method and first results of this effort. A variety of source classes, including cataclysmic variables (CVs) (see also Witham et al. 2006, 2007), early-type emission line stars (Corradi et al. 2008, 2010; Drew et al. 2008), active late-type stars, young stellar objects (Vink et al. 2008) and planetary nebulae (Viironen et al. 2009; Sabin et al. 2010) have been identified. For an example of the expected source classes and their location in the CCD, we refer to fig. 1 in Corradi et al. (2008).

The presence of an ultraviolet or X-ray photon field can ionize hydrogen atoms in its direct environment, and hence lead to an H$\alpha$ emission line in the optical spectrum. Binary systems containing a compact object, such as a white dwarf (WD), neutron star (NS) or black hole (BH), are examples of (transient) H$\alpha$ emitters, with the strength and width of the emission line depending on the primary mass, mass accretion rate and inclination angle with respect to the line of sight (Casares 2015). Other excitation mechanisms (e.g. collisional excitation in the stellar corona) can also excite H atoms and induce spectral line emission.

In addition to H$\alpha$ emission line objects, some systems show H$\beta$ in absorption. If the strength of this absorption line is stronger than that of a normal main-sequence (MS) star, it will appear as an outlier below the locus of stars in a CCD. For example, single H-rich (DA) WDs are known to exhibit a very broad H$\alpha$ absorption line. C-rich and S-type asymptotic giant branch (AGB) stars have molecular ZrO absorption bands in their spectra that coincide with the location of the H$\alpha$ line (e.g. ZrO $\lambda 6456$). These objects will hence also appear to have a deficit of flux in the H$\alpha$ filter relative to the $r'$-band and appear as outliers to the locus of objects that do not exhibit these features in their spectrum. Late-type variable stars can cover a large range in colour space depending on the relative strength of molecular absorption bands (e.g. TiO, VO, ZrO) that are located in the $r'$, $i'$ and H$\alpha$ filters.

In this work, we use the optical observations from Wevers et al. (2016a), taken as part of the Galactic Bulge Survey (GBS; Jonker et al. 2011, 2014), to search for sources with excess H$\alpha$ emission and absorption signatures compared to normal MS stars. We also identify blue outliers with respect to field stars in the CCDs. The structure of this article is as follows: Section 3 outlines the method used to identify outliers, and in Section 4, we present the results. We discuss our findings in Section 5 and summarize in Section 6.

2 DATA

2.1 Photometry

As the starting point of our work, we use the optical point source catalogue covering the GBS fields (Wevers et al. 2016a). This catalogue consists of optical photometry obtained using the Mosaic-2 camera on the Victor M. Blanco telescope, located at the Cerro Tololo Inter-American Observatory (CTIO), in three filters: $r'$, $i'$ and H$\alpha$. The areas covered are centred on $b = 1.5$ above and below the Galactic Centre, and consist of two strips spanning $(1 \times b) = (6^\circ \times 1^\circ)$. In total, 64 fields, each consisting of 8 frames, were observed twice. One of the two exposures was offset by $1.2$ arcmin in right ascension and declination to fill the gaps between the detectors. Therefore, we have 1024 observed frames in total. The mean $5\sigma$ limiting depth of the observations is $r' = 22.5$, $i' = 21.1$ mag. The point source catalogue includes objects that have been detected with a signal-to-noise ratio of more than 5 in all bands. For more details about the optical catalogue, we refer the reader to Wevers et al. (2016a).

2.1.1 Global photometric calibration

The observations consist of two strips of overlapping fields above and below the Galactic Centre, respectively (see fig. 1 in Wevers et al. 2016a). We use the overlap between these observations to apply a photometric calibration with the goal of getting all the photometry on the same absolute scale. There is no overlap between northern and southern fields, so we calibrate them independently. To this end, we use the method developed by Glazebrook et al. (1994) (see also Barentsen et al. 2014 for an application of this method to the IPHAS data set).

In short, the goal is to minimize the magnitude offsets between stars that are present on overlapping fields using a set of anchor fields for which the photometry is thought to be well determined. The reference fields are chosen on two photometric nights, namely MJID 53912 and 59315 (see table 1 in Wevers et al. 2016a and Section 3.4). We denote the magnitude offset between stars on overlapping fields as $\Delta ij = (m_i - m_j)$. In order to keep the solution from drifting arbitrarily far from the values of the anchor fields, the difference in zero-point values across the fields is also minimized. This problem can be solved as a linear least-squares problem because the magnitudes and the zero-points are linearly related. Following Glazebrook et al. (1994) and setting the weights $w_{ij} = 1$, we minimize the sum:

$$S = \sum_{i=1}^{N} \sum_{j=1}^{N} \theta_{ij} (\Delta_{ij} + a_i - a_j)^2$$

where $\theta_{ij}$ is an overlap function that is 1 when there is overlap and 0 otherwise, $a_i$ are the zero-points to solve for and $a_j$ the zero-points of overlapping fields to $a$. $N$ is the total number of fields included in the least-squares problem.

Minimizing the sum in equation (1) by varying $a_i$ is equivalent to solving $\partial S/\partial a_i = 0$, which yields the matrix equation

$$\sum_{j=1}^{N} A_{ij} a_j = b_i,$$

where

$$A_{ij} = \theta_{ij} - \delta_{ij} \sum_{k=1}^{N} \theta_{jk}$$

and

$$b_i = \sum_{j=1}^{N} \theta_{ij} \Delta_{ij}.$$

We now solve the least-squares problem by keeping the solutions of the anchor fields fixed, while the zero-points of the other fields are allowed to vary to optimize the solution as a global photometric calibration.

2.1.2 Colour–colour diagrams

Before we move to the details of the selection criteria for outliers, we first introduce the necessary tools we will use to find them:
Candidate Hα outliers towards the GBS

Figure 1. The black points show the observed colours of sources on field S01 (detector 2). The dashed lines are the spectral sequences of unreddened MS stars from O5V to M5V, with $E(B-V) = 0$ and 1 for orange squares and blue triangles, respectively. The red diamonds show colours of giants with spectral types ranging from O8III to M5III, reddened to $E(B-V) = 2$. The green squares show the early A-type MS line, which indicates the lower limit for A0V MS stars in the CCD. The arrow indicates the effect of reddening $\Delta E(B-V) = 1$. The two outliers marked by black stars around (0.1,0) are very blue compared to the other field stars, making them potentially interesting sources.

CCDs and synthetic photometry. We merge the nominal and offset observations in each filter (taken within minutes of each other), and create $(r'-i', r'-\text{H} \alpha)$ CCDs. This gives us a total 512 frames that form the basis of our work. We exclude sources with saturated photometry in our analysis. We use the same basic techniques as presented by the IPHAS collaboration (Drew et al. 2005; Witham et al. 2006).

We use a set of synthetic spectra (Pickles 1998) to create synthetic photometry for spectral types ranging from O5V to M5V using the CTIO filters.\(^1\) We redden these spectra with increasing $E(B-V)$ to estimate the colours of stars at a range of reddening values (hence distances). We consider solar-metallicity MS and giant stars. The binning of the spectra is sufficiently small (5 Å) that we can use them to compute synthetic photometry for our $r'$ and $i'$ filters as well as for the narrow-band Hα filter. We recompute the grids of these filter profiles to match the binning of the spectra, meaning that for each spectral bin we compute the filter transmission value at the midpoint of the bin. We define the synthetic colours in the Vega system as

$$m_1 - m_2 = -2.5 \log \frac{\int T_{1,\lambda} F_\lambda d\lambda}{\int T_{1,\lambda} F_{\lambda, V} d\lambda} + 2.5 \log \frac{\int T_{2,\lambda} F_\lambda d\lambda}{\int T_{2,\lambda} F_{\lambda, V} d\lambda} \quad (5)$$

where the filter transmission profiles are labelled $T_x$; $F_x$ is the synthetic spectrum per spectral type and $F_{\lambda, V}$ is the spectrum of Vega (Bohlin 2007). It is possible to compute an upper limit to the $r'-\text{H} \alpha$ colour of any physical object based on synthetic photometry of a pure Hα emission line spectrum (Drew et al. 2005). The upper limit is $r'-\text{H} \alpha = 3.3$ for the used filter combinations, hence we discard all objects that have an observed $r'-\text{H} \alpha$ colour above this value. Such values are indicative of a bad cross-match between the three optical bands, or detector artefacts.

In Fig. 1, we show an example of a CCD of field S01 (detector 2), centred at Galactic coordinates $(l, b) = (-2.81, -1.75)$. Observed colours are plotted in black, and overlaid are synthetic tracks for MS stars (orange squares and blue triangles with $E(B-V) = 0$ and 1, respectively) and giants (red diamonds, $E(B-V) = 2$). The two main populations of stars that can be identified are the unreddened MS stars (located slightly to the right and below the orange synthetic track) and the locus of reddened stars. We note that in the CCD, there is an offset between the synthetic track and the observed unreddened MS. This offset shows that the unreddened MS in this case is nevertheless slightly reddened to about $E(B-V) \leq 0.5$.

Comparing the observed CCD and the unreddened synthetic track reveals that our catalogue apparently contains no unreddened stars of early spectral types. The observed unreddened MS population typically contains only stars of spectral type KOV or later. Taking the absolute magnitude from Schmidt-Kaler (1982) and colour from

Estimated distance ranges for MS stars of different spectral types in field S01 (detector 2).

<table>
<thead>
<tr>
<th>Sp. type</th>
<th>$M_r$</th>
<th>$(r' - i')_{\text{syn}}$</th>
<th>$d$ (kpc)</th>
<th>$A_r$</th>
<th>$(r' - i')_{\text{obs}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A0V</td>
<td>0.77</td>
<td>0</td>
<td>2.6–5</td>
<td>4.4–8.4</td>
<td>1.1–2.2</td>
</tr>
<tr>
<td>G0V</td>
<td>4.26</td>
<td>0.39</td>
<td>1.3–3.4</td>
<td>2.2–5.7</td>
<td>1.0–1.9</td>
</tr>
<tr>
<td>K0V</td>
<td>5.67</td>
<td>0.48</td>
<td>0.9–2.8</td>
<td>1.5–4.7</td>
<td>0.9–1.7</td>
</tr>
<tr>
<td>M0V</td>
<td>11.72</td>
<td>0.96</td>
<td>0.5–1.8</td>
<td>0.8–3.0</td>
<td>1.2–1.8</td>
</tr>
</tbody>
</table>

Figure 2. Estimated distance ranges for MS stars of different spectral types present in the optical GBS catalogue, assuming a saturation limit of $r' = 17$ (upper horizontal dashed line) and a limiting magnitude of $r' = 22.5$ (lower horizontal dashed line). See Section 2.1.2 for details.

Pecaut & Mamajek (2013), and the colour transformation given by Jester et al. (2005), we find that a K0V star observed at $r' = 17$ (the typical saturation limit of the optical catalogue) is located at a distance of $\sim 1$ kpc. Unreddened stars with a spectral type earlier than K0V (hence intrinsically brighter) and located within 1 kpc are saturated. The photometric observations of saturated sources are unreliable and we discard them in our analysis.

We use the absolute magnitudes from Schmidt-Kaler (1982) together with the 3D reddening map from Schultheis et al. (2014) at $(l, b) = (-2.8, -1.8)$ to estimate the distance ranges for stars of different spectral types in our catalogue. The 3D reddening map is converted to the $r'$-band following Schlegel, Finkbeiner & Davis (1998). In Table 1, we show the results for different spectral types.

We use the distance modulus to estimate the observable distance range as:

$$\log d (\text{pc}) = 0.2 \times (r' - M_r - A_r(d) + 5)$$

where $M_r$ is the absolute magnitude, $r'$ the apparent (observed) magnitude and $A_r$ the extinction in the $r'$-band obtained from the Schultheis et al. (2014) reddening map. The results of this calculation are visualized in Fig. 2. We assume that the saturation limit of our catalogue is $r' = 17$, and the limiting magnitude is $r' = 22.5$ (marked by dashed horizontal lines), giving rise to the ranges shown in Table 1. Using our synthetic photometry, we can also infer the range of $r' - i'$ colours that different spectral types occupy in the CCD, assuming that $E(r' - i') = 0.26 \times A_r$. (Schlegel et al. 1998).

We conclude that the locus of reddened stars at $r' - i' \sim 1.4$ consists of reddened MS stars with spectral type earlier than M0V. The objects located beyond $r' - i' \sim 2$ are giants, as MS stars are too faint to be observable at those reddening values.

We briefly note that there are two outliers around $(r' - i', r' - H\alpha) = (0.1,0)$. As we explained above, these can not be ordinary early-type MS stars because they would appear saturated in our observations.

2.2 Spectroscopy

A 500 s spectrum of the optical counterpart to the X-ray source CX2 (Jonker et al. 2011) was taken on 2010 July 8 with the ESO Faint Object Spectrograph and Camera (EFOSC2; Buzzoni et al. 1984) at the ESO New Technology Telescope (NTT). We used grism no. 13 combined with a 1 arcsec slit, resulting in a spectral resolution of $R \sim 300$ and a wavelength coverage ranging from 3700 – 9300 Å. We debiased and corrected for the CCD flat-field response, and wavelength calibration was performed using a HeAr arc lamp. We normalized the spectrum by fitting cubic splines to the continuum in MOLLY.

3 OUTLIER IDENTIFICATION

We devised a selection method that results in the automatic identification of H\alpha emission and absorption line candidates and blue sources (all referred to as outliers). Our data set consists of 1024 observations, observed on eight nights, spanning a large range of stellar densities, dust extinctions and photometric uncertainties. Hence, it is unavoidable that any selection method will fail in some cases. We take a conservative approach and prioritize minimizing false positives over completeness. This implies that our catalogue will not be complete. Below we introduce the automatic identification algorithm together with a list of criteria that must be fulfilled for the results to be deemed trustworthy. CCDs that fail to meet these criteria have been rejected from automatic processing and are instead inspected manually.

We set out to identify the outliers from the main features that are present in the CCD: the unreddened MS and reddened sequence. We make a distinction between these two features and fit them independently. We identify H\alpha emission line sources from both the unreddened and reddened loci of objects. Additionally, we identify absorption line sources from the reddened locus, which should be located below the main population in the CCD. Unreddened stars with strong absorption line features may overlap with more reddened objects (and conversely H\alpha emitters from the reddened locus may overlap with the unreddened MS) and cannot be distinguished based on a CCD alone. Including a colour–magnitude diagram in the analysis may help to break this degeneracy, but this is beyond the scope of this work.

We perform the analysis (described in detail below) for two magnitude bins, one including sources with $r' \leq 19.5$ and one containing sources with $r' \geq 19.5$. The motivation to use two magnitude bins is the fact that at fainter magnitudes, the photometric uncertainties increase and hence the scatter of stars in the CCD also increases. If we combine sources with small and large photometric errors in the same CCD, our selection criteria will be dominated by the intrinsic scatter of the faint sources. This may preclude us from identifying sources with small photometric uncertainties as significant outliers. We use the value $r' = 19.5$ because the peak of the distribution of magnitudes in the $r'$-band typically occurs around this magnitude. It is approximately in the middle between the saturation limit and the 5$\sigma$ detection limit, and roughly the completeness limit of the optical catalogue (Wevers et al. 2016a).
3.1 Outliers from the unreddened MS

We define unreddened objects as sources that have $E(B - V) \leq 1$ (i.e. all objects that lie above the synthetic track with $E(B - V) = 1$, see Fig. 1). As noted already in Witham et al. (2006), fitting a straight line to this selection of objects may not converge on to the observed unreddened MS. The solution proposed by these authors is to iteratively force the fit upwards, and we do the same here. After an initial fit to all points with $E(B - V) \leq 1$, we select the objects above the fitted line and iterate, forcing the fit up towards the unreddened MS. In practice, the shape of the CCD is determined by the detection limit of our observations, the stellar density and reddening along the line of sight. CCDs along different lines of sight have a different shape depending on these parameters, hence they require a different number of iterations for the fit to converge on to the unreddened MS. To establish whether or not our fit represents the unreddened MS, we calculate the slope of our fit in each iteration. If the slope of the fit is more shallow than the slope of the synthetic track between spectral types K5V and M5V, we deem our fit unsatisfactory and apply an additional iteration (i.e. we force the fit upwards). We iterate for a maximum of five times; CCDs for which the fit has not converged at that point will be inspected manually for outliers. We also place a constraint on the $r' - i'$ colour of an unreddened MS star, to distinguish those sources from reddened stars with Hα emission. These sources may occupy the same parameter space in the CCD. However, $r' - i'$ increases for later spectral types. We conservatively estimate from the extent of the unreddened MS in our CCDs that the highest $r' - i'$ colour an unreddened late-type MS star can have is $r' - i' = 3.5$.

Once we have identified the unreddened MS, we determine the iteratively 4σ-clipped scatter around the fit. We define outliers as sources with an excess Hα emission contribution, quantified as follows:

$$
(r' - \text{H}α)_{\text{obs}} - (r' - \text{H}α)_{\text{fit}} \geq C \times \sqrt{\sigma_i^2 + \sigma_{\text{phot}}^2}
$$

(7)

Here, $\sigma_i$ represents the scatter of data points around the fit, and $\sigma_{\text{phot}}$ is the photometric measurement error for the $r' - \text{H}α$ colour index. $C$ is a constant that we set to 4. An example is shown in Fig. 3. The resulting fit is overplotted as the upper solid line, while the dashed lines indicate the 4σ scatter. Note that this is only a mean representation of the scatter, as it differs for each individual measurement. As an illustration, we include the photometric uncertainties in $r' - \text{H}α$.

3.2 Outliers from the locus of reddened stars

For the next step, we remove all sources belonging to the unreddened MS (defined as all data points that are within 4σ of the final fit) and continue our analysis with the remaining objects. If the slope of our fit after five iterations is still more shallow than that of the synthetic photometry, we cannot identify the unreddened MS. In that case, we remove all points above the synthetic track with $E(B - V) = 1$, with the exception of sources that have $r' - i' \geq 3.5$ (as these cannot be part of the unreddened MS). We are now left with a sample of reddened stars, and continue to identify outliers by fitting a straight line to the remaining objects. As for the unreddened case, we determine the iteratively 4σ-clipped scatter to obtain the best fit and the scatter around it. For sources that are located below the locus of reddened objects (the absorption line sources), the left-hand side of equation (7) changes to an absolute value. Moreover, sources that have Hα in absorption will have a comparatively lower signal-to-noise ratio in the Hα filter (see Section 4). It is expected that the scatter of these sources in the CCD will be larger than the typical scatter of the locus of stars. We therefore use a more conservative value of $C = 5$ for the identification of absorption line candidates.

Visual inspection of the Hα absorption line candidates shows that we identify many sources that fall partially off the detector when the Hα filter is mounted but not when the $r'$ filter is present. This slight shift in the focal plane is likely introduced by the different optical path the incoming light follows when the Hα filter is mounted. To
Figure 4. Panel (a): normalized \(r' - i'\) colour distribution of all stars brighter than \(r' \leq 19.5\) on field S20, detector 6. The blue (dashed) and red (dash–dotted) lines show the Gaussian distributions; the black solid line shows the sum of both components. The vertical dashed line shows the 5\(\sigma\) limit below which sources are flagged as outliers. There are two outliers around \(r' - i' = 0.2\), marked with an arrow. Panel (b): same as panel (a), but for all stars fainter than \(r' \geq 19.5\). No blue outliers are identified.

remove these spurious sources, we require that the source position is more than 20 pixels from the detector edges.

Fig. 3 shows an example of two CCDs for the bright (panel a) and faint (panel b) magnitude bins. In particular, panel (b) illustrates the diversity of photometric measurement errors (even for stars in the same magnitude bin), which can greatly influence outlier detection. The emission line candidate from the unreddened MS is inside the mean 4\(\sigma\) boundaries, but still a significant outlier because of the very small photometric uncertainty. The emission line candidate at \(r' - i' = 3.8\) is also consistent with the expected locus of unreddened stars. However, the high \(r' - i'\) colour implies it cannot be an unreddened object, so we detect it as an outlier to the locus of reddened sources.

3.3 Blue outliers

In Fig. 3, the fit to the unreddened MS (the upper solid line) is satisfactory in panel (a), with a slope consistent with that of the unreddened MS synthetic photometry. There are two objects with very blue colours compared to the fields stars in the diagram (marked by blue squares). However, we do not identify them as outliers because they fall within the limits of the 4\(\sigma\) regions around our fitted lines. Because these are potentially interesting sources, we use a different selection algorithm based on their \(r' - i'\) colour.

We fit the distribution in \(r' - i'\) with a Gaussian mixture model using the Python Machine Learning package sci-kit learn (Pedregosa et al. 2011). Based on the shape of the histogram, which is typically single- or double-peaked, we consider two models, one consisting of one Gaussian distribution and the other consisting of the sum of two Gaussians. We note that there is no reason to believe that the blue edge of this distribution should follow a one-sided Gaussian distribution function. The shape of this colour distribution is determined by many factors, including the stellar density and magnitude distribution of stars along the line of sight, our survey detection limits and the effects of reddening. Typically, the blue edge of the distribution is sharper than Gaussian (Carmona-Ruiz et al., in preparation), hence our approximation by a Gaussian distribution is a conservative approach. We show a result of fitting two Gaussian distributions to the number of stars as a function of their \(r' - i'\) colours in Fig. 4 for the same field as in Fig. 3.

We determine the width, height and peak position using an iterative maximum likelihood estimate approach. Given the best-fitting parameters, we flag all sources more than 5\(\sigma\) away from the peak of the distribution as outliers (marked in the figure by the dashed vertical line). In the case that the sum of two Gaussians works best, we select the blue (lowest \(r' - i'\) peak position) Gaussian component to determine which sources are blue outliers.

3.4 Quality control

The methods that we employ to find outliers do not rely on any underlying physical models that accurately predict the shapes or positions of the populations of sources we are trying to describe. We have optimized our methods such that they work for the majority of the frames, but visual inspection shows that in some cases our selection procedures do not yield satisfactory results. We therefore visually inspect every CCD to reject all anomalous frames.

First of all, there are 75 frames for which the slope of our fit after five iterations is still more shallow than the slope of the synthetic track. As was mentioned earlier, this can arise due to a combination of the stellar density and reddening along the line of sight, together with our selection criteria for (un)reddened objects. In nine cases, the iterative procedure reduced the number of stars available for the fit to only a handful. Visual inspection shows that no outliers were missed in these frames. In the remaining 66 frames, the upper part of the population in the CCD is well identified, even though the slope is more shallow than our threshold value. The outliers we find in these frames are robustly identified and included in the final sample.
Secondly, the presence of HII regions can affect the CCD by increasing the number of apparent Hα emission line sources due to increased non-homogeneous extended emission. This is the case in fields S04 and N15. In SIMBAD, we find HII regions LBN1120 and LBN9 for S04 and N15, respectively. The CCDs of field S07 contain a very large number of Hα emission and absorption line outliers. We find an open star cluster in this field, containing many bright ($V \sim 6$) stars that are saturated in our observations. We attribute the large number of outliers to the presence of these bright stars, which cause blooming of charge in the detectors that lead to false source detections and colours, and/or erroneous matches (see Wevers et al. 2016a for a discussion about the effect of saturated sources on e.g. source detection).

Figure 5. Magnitude and colour distribution of the sample of candidate Hα emission (left three panels) and absorption (right three panels) line outliers. An explanation for the decreased number of outliers in the magnitude bin $19.5 \leq r' \leq 20$ is given in the text.

Figure 6. Same as Fig. 5, but for the blue outliers.

4 RESULTS

4.1 Outlier populations

We find a total of 389 blue outliers, 336 absorption line candidates and 1337 emission line candidates in our photometric catalogue. We show the magnitude and colour distributions of the emission and absorption line candidates in the left- and right-hand panels of Fig. 5, respectively. We identify 62 sources that are both blue and have signs of excess Hα emission. We also find three sources that are blue and candidate Hα absorption sources. The sample properties of the blue outliers are shown in Fig. 6. The distribution of emission line candidates, in particular the decrease of the number of outliers in the bin $19.5 \leq r' \leq 20$, is introduced by the division into two magnitude bins at $r' = 19.5$. The increase of Hα emission line candidates up to $r' = 19.5$ can be explained by two effects: an increasing number of stars at fainter magnitudes, and an increased occurrence of emission line sources at fainter magnitudes. For the fainter magnitude bin, the intrinsic scatter of stars is much larger (due to the larger measurement errors), leading to a reduction in the number of observed outliers compared to the bright bin.

Similarly, there is a large decrease in the number of absorption line candidates for $r' \geq 19.5$. This can be understood as a combination of two effects. As mentioned above, the increased scatter for faint stars decreases the number of outliers we identify. Moreover, absorption line candidates have a lower flux in the Hα filter, hence they are detected with a lower signal-to-noise ratio compared to other sources with similar $r'$-band magnitudes. This means that it is much harder to detect absorption line candidates at fainter magnitudes, and results in a strong decrease in the number we can identify.

Table 2 shows an example of the information available for the outliers. The full tables can be found in the online material, and will also be made available in electronic form through the Vizier database (http://vizier.u-strasbg.fr). Here, we will include the outlier catalogues described above, and in addition, we will add outlier samples with slightly less restrictive selection criteria. In particular, we will add an emission line catalogue that includes all 3σ outliers and a catalogue of blue outliers with a 4σ selection limit.

4.2 Optical counterparts to X-ray sources

Now that we have identified the outlier candidates in the optical photometry, we cross-correlate the sample with the GBS X-ray sources from Jonker et al. (2014). We use the 4σ X-ray error circle, defined in Wevers et al. (2016a), as the cross-matching radius. We find 13 matches among the emission line candidates, while for the absorption line candidates we find one potential counterparts and among the blue outliers we find two matches. In Table 3, we present the optical counterparts.
Table 2. Example of the tables containing the information of the sources identified as outliers, including the position, magnitudes and colours. The photometric measurements are quoted in Vega magnitudes.

<table>
<thead>
<tr>
<th>RA (°)</th>
<th>Dec (°)</th>
<th>i'</th>
<th>σ_i'</th>
<th>l</th>
<th>σ_l</th>
<th>Hα</th>
<th>σ_Hα</th>
<th>i' − l</th>
<th>r' − i'</th>
<th>r' − Hα</th>
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Table 3. Properties of the optical counterparts (identified as outliers) to GBS X-ray sources. The position of the optical counterpart is given in degrees. The uncertainties of these positions can be found in Wevers et al. (2016a). All magnitudes are given in the Vega system. The numbers in brackets correspond to the uncertainty on the last digit. EW is the equivalent width of the Hα line in Å, where a negative value indicates emission. In the comments, we give the classification (if available) and the most relevant reference work. DN stands for dwarf nova, IP for intermediate polar, qLMXB for quiescent low-mass X-ray binary and Sy1 for Seyfert 1 galaxy.

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<th>σ_i'</th>
<th>l</th>
<th>σ_l</th>
<th>Hα</th>
<th>σ_Hα</th>
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<th>r' − i'</th>
<th>r' − Hα</th>
<th>EW</th>
<th>( \frac{F_X}{F_{opt}} )</th>
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5 DISCUSSION

5.1 Optical counterparts to X-ray sources

A significant fraction of the optical counterparts to X-ray sources found in this work have already been classified. In this regard, of the 13 emission line candidates, 7 have been previously studied and classified as CVs, 3 of which are magnetic systems (Table 3). This is not surprising, since magnetic systems are known to have a higher X-ray to optical flux ratio, so they can be detected at larger distances (in X-rays) compared to non-magnetic CVs. In addition, two Hα emission line objects were identified as dwarf novae, while the remaining two are a dwarf nova candidate and either a CV or a qLMXB, respectively. One background AGN was identified as an Hα absorption line candidate, and one blue outlier was classified as a high-state AM CVn system.

5.2 Multiwavelength counterparts

A number of observing programs with arcsecond spatial resolution have imaged the Galactic bulge, producing source catalogues that are potentially useful to further constrain the nature of objects in our sample. Below, we give a brief overview of the wavelength coverage and properties of some of these catalogues. A detailed study of multiwavelength cross-matches with our catalogues is beyond the scope of this paper.

At optical wavelengths, the OGLE survey (Udalski, Szymański & Szymański 2015) has observed a large part of the Galactic bulge during multiple observing seasons with a cadence on occasion as short as 20 min, adding temporal information to our optical colours. In the near future, VPHAS+ (Drew et al. 2014) will complement our observations by adding catalogues in the u', g' and z' bands, as well as temporal colour and astrometric information on a ~10 yr baseline. For some sources, proper motion measurements are available (e.g. Sumi et al. 2004, Fedorov, Myznikov & Akhmetov 2009). Narrow-band Hβ 5875 Å information is also available from the UV EXcess survey (Groot et al. 2009). Other catalogues that overlap include the XMM–Newton serendipitous UV survey catalogue (Page et al. 2012), while the Vista Variables in the Via Lactea survey (Saito et al. 2012) and UKIDDS (Lucas et al. 2008) surveys can constrain the NIR part of the spectral energy distribution. Part of the GBS footprint coincides with mid-IR catalogues such as the Spitzer Bulge catalogue (Uttenthaler et al. 2009). At optical wavelengths, the Spitzer survey (Page et al. 2012) and the VISTA Variables in the Via Lactea survey (Saito et al. 2012) and UKIDDS (Lucas et al. 2008) surveys can constrain the NIR part of the spectral energy distribution. Part of the GBS footprint coincides with mid-IR catalogues such as the Spitzer Bulge catalogue (Uttenthaler et al. 2010), the GLIMPSE catalogue (Spitzer Science 2009) and AllWISE catalogues (Ochsenbein, Bauer & Marcout 2000).
5.3 CCD of outliers

We discuss the CCD of all the outliers and the implications for the identification of different source classes in the diagram. We show the position of all outliers in the CCD in Fig. 7. The emission line candidates are plotted as grey triangles, while blue outliers are marked as blue circles and absorption line candidates are shown as green diamonds. Counterparts to GBS X-ray sources are marked as red stars. The gap between emission and absorption line sources marks the global position of the locus of objects in all GBS fields.

5.3.1 Emission line sources

We interpret the spread of the emission line candidates (in $r' - H\alpha$) as two different populations. The largest population consists of the outliers from the unreddened MS, and constitutes the upper population of emitters. In addition to these, another track of outliers at lower $r' - H\alpha$ with a shallower slope can be identified. These systems are likely reddened stars with $H\alpha$ in emission.

We expect the sources that have $r' - i' \leq 1$ and $H\alpha$ in emission (the region of overlap between the blue outliers and emitters) to be good (non-magnetic) CV candidates. At somewhat redder colours, we expect other $H\alpha$ excess sources such as intermediate polars (IPs) and (quiescent) LMXBs. For example, NS LMXBs and long-period BH LMXBs are more X-ray bright, hence they can be detected further out in X-rays and their optical colours will be reddened by interstellar dust extinction. Intrinsically more red objects such as flare stars, and other sources such as chromospherically active (binary) stars and early-type emission line stars are also expected to be found as $H\alpha$ emitters. Planetary nebulae, whose spectrum is dominated by emission lines with a low continuum contribution, should show up as very large $H\alpha$ excess sources up to the $r' - H\alpha = 3.3$ limit.

Cross-matching these sources with the SIMBAD data base yields a variety of sources (Table 4), indicating that indeed our sample could span the whole range of stellar evolution. We find, among others, two young stellar object candidates, five variable stars, two AGB candidates and four systems containing a WD.

5.3.2 Blue sources

The population of blue outliers likely consists of systems containing a compact object such as a WD, NS or BH. Nearby early-type MS stars are saturated in our observations, hence they cannot populate the blue part of the CCD. Although some outliers have bluer colours than field stars in the CCD, their colours are not extremely blue. The median ($r' - i'$) colour is 0.26, and because $r' - i'$ increases with distance (due to interstellar dust extinction), we expect the blue sources to be relatively close to Earth. The differential reddening in the $r'$-band with respect to $i'$ is $\Delta(r' - i') = 0.26 \times A_{r'}$ (Schlegel et al. 1998), where $A_{r'}$ is the extinction in the $r'$-band (in mag). Assuming an intrinsic colour of $r' - i' = 0$ (corresponding to an A0V spectral type, and typical for a blackbody spectrum with $T \sim 10,000$ K), this implies a typical reddening of $A_{r'} \sim 1$ mag that in turn means that the source should be nearby $\lesssim 1$ kpc.

Blue outliers are identified up to $r' - i' = 1$, indicating that we are not just finding foreground objects but also systems at distances where the dust extinction, becomes appreciable ($A_{r'} \sim 4$ mag). For example, in some lines of sight with low extinction background AGN may be part of the blue outlier population. Some of the (dust) extinction may also be intrinsic to the system. Hot subluminous dwarfs (sdO/B stars) are also expected to be found as blue outliers with respect to field stars. Typical hot subdwarf stars fainter than $g = 17$ mag have distances exceeding 4 kpc (Geier et al. 2011), implying that these blue objects could appear as some of the reddest of the blue outliers. The sample of 62 blue outliers that are also...
Table 4. Source identifications from the SIMBAD data base. We used a search radius of 2 arcsec around the position of the optical source in question (\Halpha emission or absorption line or blue outlier). The right ascension and declination of the GBS sources are given in degrees. Type gives the identification: X stands for X-ray source, RR signifies RR Lyrae star, DN means dwarf nova, YSO? and AGB? indicate a young stellar object candidate and AGB candidate, respectively. Em stands for emission line object, PN for planetary nebula, DQ for DQ Her type CV and SRV for semi-regular variable star.

<table>
<thead>
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Absorption line sources

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Blue sources

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5.3.3 Absorption line sources

Regarding the absorption line candidates, we expect them to include late-type stars and variable stars such as Mira giants and AGB stars. Late-type stars can have strong ZrO absorption bands that coincide with the H\alpha filter (e.g. Castelaz & Luttermoser 1997). This deficit of flux in the H\alpha filter relative to the r′-band shifts the sources below the main locus of objects in the CCD. Wright et al. (2008) investigated the nature of extremely red objects discovered in the IPHAS survey, and found that they contain a large sample of C-rich and S-type AGB stars. Similarly, we expect red sources (r′ − i′ ≥ 2.5) with an excess H\alpha absorption signature (r′ − H\alpha ≤ 1) to comprise C-rich and S-type AGB stars. The range of r′ − H\alpha colour index originates in the relative strengths of different molecular absorption bands (in particular TiO, VO and ZrO) for varying surface chemistries.

In addition to variable stars, we expect another group of sources to populate this area in the CCD. We illustrate this using CX2, which was classified as a Seyfert 1 (Sy1) galaxy at a redshift of z = 0.0214 (Marti et al. 1998; Jonker et al. 2011; Maccarone et al. 2012). In this work, we have identified it as an H\alpha absorption line source, which seems contradictory as Sy1 galaxies are known to have broad H\alpha emission lines in their spectra. Fig. 8 shows an EFOSC2 optical spectrum of CX2. Overplotted are the r′, i′ and H\alpha filter profiles. The H\alpha emission line of CX2 has been redshifted outside of the narrow H\alpha filter bandpass and instead falls in the r′ filter. Consequently, the source is brighter in r′ relative to H\alpha, and falls in the region below the locus of sources in the CCD.

An estimate of the redshift range for which this effect is at play can be obtained as follows. The width of our H\alpha filter profile is ∼100 Å. Assuming an H\alpha emission line FWHM in a Seyfert 1 galaxy of ∼100 Å (Winkler 1992), this effect will cause AGNs with redshifts between z = 0.015 and z = 0.06 to potentially show up as absorption line sources (the exact boundaries depending on the FWHM of the emission line). We thus expect that part of the background AGN population with a strong H\alpha emission line could show up in our photometric search as candidate absorption line sources. More generally speaking, different subclasses of AGN exhibit multiple strong emission features (e.g. H β, [O II] λ3727 and [O III] λ5007) that, if at the right redshift, can fall into the r′-band. This means that there are multiple redshift ranges, depending on which strong emission features are present in the spectrum, where the source could appear as an H\alpha absorption line object. Similarly, AGNs with the right redshift may show up as H\alpha emission line objects due to emission lines other than H\alpha.

6 SUMMARY

We use optical photometry in three filters (r′, i′ and H\alpha) to create (r′ − i′, r′ − H\alpha) CCDs of point sources in the GBS fields (Jonker et al. 2011, 2014; Weyers et al. 2016a). The optical source catalogue reaches a mean 5σ depth of r′ = 22.5, i′ = 21.1. The CCDs are used to systematically search for outliers in colour space, specifically H\alpha emission and absorption line sources. We also use the r′-i′ colour distribution to search for blue outliers with respect to field stars. We identify 1337 emission line candidates, 336 absorption line candidates and 389 blue outliers in the catalogue. These samples likely contain a plethora of sources, ranging from chromospherically active stars, subluminous hot dwarfs, WDs, CVs, planetary nebulae,
LMXBs and variable stars to background AGN. There is overlap between the blue and emission line candidates in 62 objects, and 3 blue sources are identified as having excess Hα absorption. We cross-match our outlier samples with the catalogue of GBS X-ray sources (Jonker et al. 2014), and find that 16 outliers are counterparts to X-ray sources. 10 of those were previously classified based on photometric and/or spectroscopic follow-up. Four emission line candidates are classified as (magnetic) CVs, two as dwarf novae (and one DN candidate) and one system is a CV/qLMXB candidate. One of the absorption line candidates is a background AGN, and one blue outlier was classified as a high-state AM CVn system. Spectroscopic observations of a representative sample of sources are needed to determine the completeness and sensitivity to the EW of our method. Individual source classifications require spectroscopic observations. The panchromatic coverage of the GBS area, including X-ray, UV, optical and IR observations, can greatly facilitate a targeted search for specific source classes.

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SUPPORTING INFORMATION

Supplementary data are available at MNRAS online.

Absorbers.pdf
Bluesources.pdf
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