

Homogeneous Distances to Several Stellar Groups in the Second Galactic Quadrant

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ABSTRACT

A photometric study in the $uvby\beta$ system of a $20^\circ \times 20^\circ$ field in direction of the Cas OB6 and Per OB1 associations is presented. All currently available $uvby\beta$ photoelectric data are used to obtain homogeneous color excesses and distances of nearly 230 stars of spectral types O-B9. The double cluster η & χ Per, NGC 663 and NGC 1502 are well represented in our sample. The sample also contains the brightest members of the young open clusters IC 1805, IC 1848, St 2, St 7 and ASCC9. We found that, within the errors, η & χ Per, NGC 663, IC 1805, IC 1848 and ASCC9, together with the Per OB1 association are located at very similar distance moduli between 11.0 to 11.3 mag. Our results indicate that the distance spread among these objects is less than the previously estimated, suggested that they could represent star-forming complexes located at the same distance.

Keywords: Open Clusters and Associations: Individual (NGC 869); Open Clusters and Associations: Individual (NGC 884); Open Clusters and Associations: Individual (Per OB1); Open Clusters and Associations: Individual (NGC 663); Open Clusters and Associations: Individual (NGC 1502)

1. Introduction

The central part of the second Galactic quadrant, located between 125° and 145° galactic longitude and -10° and 10° galactic latitude contains several isolated HII regions. Among them, Sh 2-190 and Sh 2-199 are the most prominent, found toward $l = 135^\circ$ in the disk. Several very young clusters (IC 1805, 1848 and Col 33) are associated with these nebulae. The sparse Cas OB6 association, which may be part of the even more extended Cam OB1 is also in this direction. The relatively compact Per OB1, surrounding the double cluster η and χ Per, is located several degrees below the disk. Other clusters, among which NGC 663 are found in an area free of $H\alpha$ emission toward $l = 130^\circ$. The field presents a unique opportunity to study possible co-evolution of stellar clusters and associations. Some of the populated clusters, especially η and χ Per, have been extensively investigated both in terms of broad-band (UBV, VI) and intermediate-band ($uvby\beta$) photometries.

The purpose of this paper is to provide an overview of the structure of the field based on homogeneous distance and reddening estimates for as many young stars as possible. For our purpose we utilize the $uvby\beta$ system (Strö-

mgren [1], Crawford & Mander [2]) which is arguably better suited to the study of individual stars in terms of stellar luminosity than any other system in wide use. The $uvby\beta$ photometry-derived parameters allow reliable distance determinations, thereby helping to distinguish between closely spaced groups lying along the line of sight. It should be also noted that the distance determination in the $uvby\beta$ system, when based on early-type stars, is metallicity independent. This helps to reduce the uncertainties in the cluster distances in comparison to those obtained via main-sequence (MS) fitting, where an assumption regarding the metallicity is necessary.

This is the first article of a series of papers dedicated to the structure of the second Galactic quadrant, as delineated by open clusters and OB associations for which homogeneous $uvby\beta$ photometric distances can be derived.

2. The Sample

All $uvby\beta$ data within the studied coordinate range was extracted from the Hauck & Mermilliod catalog [3]. The sample contains 226 stars of spectral types O to B9 with complete $uvby\beta$ photometry. **Figure 1** presents these

stars overplotted on a $H\alpha$ map (smoothed to 4 arcmin resolution to remove star residuals, Gaustad *et al.* [4]), obtained via the *SkyView* VO interface (McGlynn *et al.* [5]).

3. Calculation of Interstellar Extinction and Distances

In order to infer stellar parameters from the photoelectric photometry, we follow the procedure described in detail by Kaltcheva & Hilditch [6]. The spectral and luminosity

classifications (MKK) were extracted from the SIMBAD database and used in conjunction with the classification $[c_1]$ vs. $[m_1]$ diagram (Strömgren [1], not shown here). Only stars with $[m_1]$ smaller than 0.15 are used in the following analysis, since photometrically they should be earlier types than B9. We found a good agreement between the photometric classification and the MKK types. Note that in the $uvby\beta$ system both the color excess $E(b - y)$ and absolute magnitude (M_V) calculations do not rely on a precise determination of the spectral subtype, since the calculations are carried on in the same

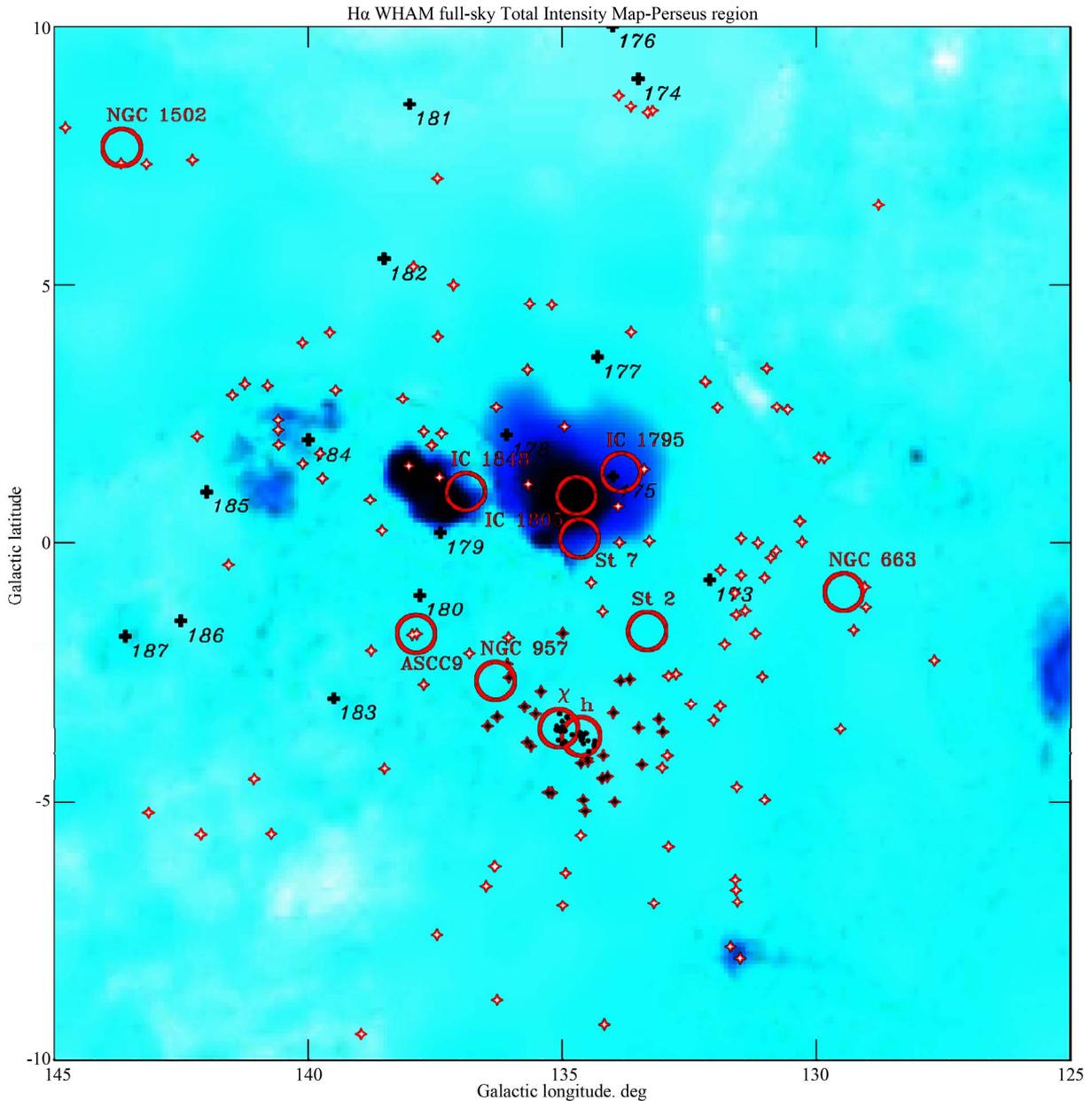


Figure 1. All stars in the field with $uvby\beta$ photometry available in the Hauck & Mermilliod catalog [3] plotted in galactic coordinates (longitude and latitude, in degrees). The stars are superimposed on a $H\alpha$ obtained via the *SkyView* VO interface. The open clusters with $uvby\beta$ photometry are shown with large circles and are labeled. The star-forming complexes by Russeil [26], also labeled, are marked with plus symbols.

way for all stars in a given spectral range (e.g. O-B9), depending only on the luminosity class (LC). This reduces the errors when calculating these parameters in comparison to the spectrophotometric method.

We used the Crawford's [7] calibration to obtain the color excesses for LC III, IV and V. The calibration by Kilkenny & Whittet [8] was used for LC II, Ib, Iab and Ia. We adopted $R = 3.18$ and $E(B - V) = E(b - y)/0.74$ to obtain V_0 . The calibration by Balona & Shobbrook [9] was utilized for all stars to derive the M_V values. Since we are dealing with early spectral types, the presence of emission lines in the stellar spectra is the largest source of error in the calculated absolute magnitudes. However, the β vs. c_0 diagram (not shown here) reveals that very few stars deviate from the main sequence and have photometry affected by emission. Note that the outlined procedure provides photometric distances in excellent agreement with the recalculated *Hipparcos* data (Kaltcheva & Makarov [10]). In addition, the Balona & Shobbrook [9] luminosity calibration has been tested via the *Hipparcos* data and shown to be reliable (Kaltcheva & Knude [11], Torra *et al.* [12], Kaltcheva & Golev [13]). The expected uncertainties in M_V are of the order of ± 0.3 mag for O and B types of LC III-V, and ± 0.5 mag for B-type supergiants. An uncertainty of ± 0.3 mag in M_V propagates to an asymmetric error of -13% to $+15\%$, and uncertainties of ± 0.5 mag result in -21% to $+26\%$ error in the derived distances.

4. Photometry-Derived Results

The derived stellar parameters for the sample stars are available from the authors upon request. The diagrams color excess $E(b - y)$ vs. distance moduli (DM), V_0 vs. $(b - y)_0$ and M_V vs. $(b - y)_0$ were examined to reveal spatially coherent structures in the studied longitude range.

4.1. h and χ Per and Per OB1

The first extensive *uvby β* photometry of h and χ Per (NGC 869 and NGC 884, respectively) was performed by Crawford *et al.* [14]), who concluded that both clusters have nearly the same age and distance, the distance modulus being 11.4 ± 0.4 mag. Balona & Shobbrook [9] corrected this value for evolutionary effects and adopted a distance modulus of 11.16 for both clusters. Marco & Bernabeu [15] presented *uvby β* CCD photometry of nearly 350 stars in the area of the cluster, to a limiting magnitude $V = 16.5$. From ZAMS fitting, they derived a distance moduli of 11.66 ± 0.20 and 11.56 ± 0.20 for h Per and χ Per, respectively, and adopted 11.60 ± 0.20 to the double cluster. Based also on *uvby β* CCD photometry, Capilla & Fabregat [16] found that both clusters share a common distance modulus of 11.7 ± 0.1 mag. However, analyzing *uvby β* literature data, Malysheva [17] obtained

different distances to the clusters (2025 pc to NGC 869 and 2426 pc to NGC 884—distance moduli 11.53 and 11.92 mag respectively).

The findings based on broad-band photometry seem to be a little bit more controversial. Based on CCD UBV data and spectroscopic parallaxes Slesnick *et al.* [18] obtained a distance modulus of 12.5 ± 0.5 mag for objects within the cluster cores, but including only stars brighter than $V = 10.5$ mag yielded 11.95 ± 0.2 . Their best-fitting distance modulus provides 11.85 ± 0.05 mag, corresponding to a distance of 2344 ± 54 pc. Currie *et al.* [19] presented very extensive VI photometry and spectroscopy of h & χ Per down to sub-solar masses. They found both clusters, as well as the halo, to have similar color excesses ($E(B - V) = 0.52 - 0.55$) and distance moduli ($DM = 11.8 - 11.85$ (for $R = 3.12$)). These estimates lead to a distance of 2300 - 2350 pc. The most recent catalog of open clusters Kharchenko *et al.* [20] lists a distance of 2079 pc to NGC 869 and 2345 pc to NGC 884, estimates currently accepted in the WEBDA database. Selected values of distance modulus, age and reddening taken from the literature have been recently systematized by Southworth *et al.* [21] and also by Currie *et al.* [19]. In general, some authors claim that h Per (NGC 869) is closer and younger than χ Per (NGC 884), while other state that the clusters have similar distance and age.

The double cluster is sometimes considered to be the core of the Per OB1 association. Humphreys [22] identified 105 members of the association within longitude range from 132° to 136° and latitude from -5° to -2.5° , at a distance modulus 11.83 ± 0.06 . Using the cluster-fitting method, Garmany & Stencel [23] derived a distance modulus of 11.8 for related members. The Per OB1 members identified by the latter authors span a larger range in Galactic longitude (131° to 139°) and Galactic latitude (-6.5° to 0°). It is a long-standing question whether or not the double cluster is spatially connected to Per OB1 (see for example the discussion in Slesnick *et al.* [18]). Although containing more than 10 O-type stars, Per OB1 is not associated with any known HII regions or giant molecular cloud (see Lee & Lim [24] for a thorough discussion).

In a $3^\circ \times 3^\circ$ field toward the cluster, there are 82 O and B-type stars with photometry available in the Hauck & Mermilliod catalog [3]. It should be mentioned that for h and χ Per and Per OB1 the available *uvby β* photometry of the vast majority of stars comes from a single source, namely Crawford *et al.* [14] and is thus very homogeneous. The diagrams color excess $E(b - y)$ vs. Distance Modulus, V_0 vs. $(b - y)_0$ and M_V vs. $(b - y)_0$ are presented in **Figure 2**. The stars are shown with different symbols as follows: open squares for NGC 869; open circles for NGC 884; filled symbols for the stars of the sur-

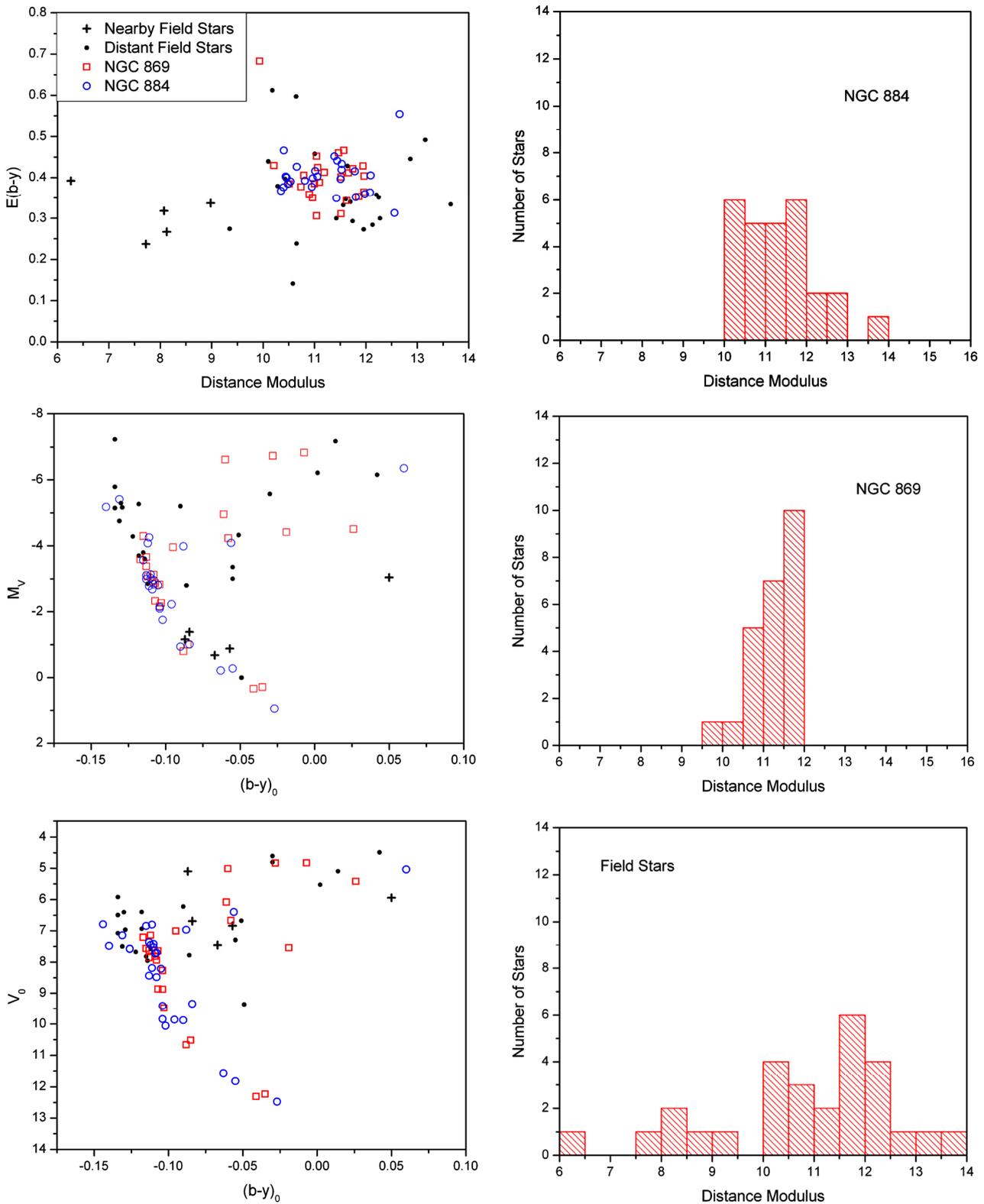


Figure 2. All O-B9 stars with calculated distances and color excesses in the sample in the field of Per OB1 association. (Left) The diagrams color excess $E(b - y)$ vs. Distance Modulus, V_0 vs. $(b - y)_0$ and M_V vs. $(b - y)_0$. The cluster stars and the field stars are plotted with different symbols as follows: open squares: NGC 869; open circles: NGC 884; plus symbols: nearby field stars; filled symbols: distant field stars. (Right) The histograms of the individual distances of NGC 869, NGC 884 and the field stars.

rounding Per OB1 association; plus symbols for the several nearby field stars. The average distance moduli and color excesses for NGC 869, NGC 884 and Per OB1 are presented in the first part of **Table 1**. According to this sample, the clusters are located at the same distance (we adopt 11.23 ± 0.6 s.d.) and have similar excess ($E(b - y) = 0.40 \pm 0.05$). These results are consistent with both following Balona & Shobbrook [9] and Crawford *et al.* [14]). The estimated distance to Per OB1 is similar to the distance to the clusters, although a larger spread of the individual distance moduli can be seen, as expected for an OB association. However, the average distance to the association is more sensitive to the completeness of the sample, in comparison to the average distances of the clusters. The V_0 vs. $(b - y)_0$ and M_V vs. $(b - y)_0$ diagrams are also indicative for a similar distance and, to a large extent, stellar content for both the clusters and the surrounding stars. It could be noticed, that NGC 869 contains nearly three times more evolved stars in comparison to NGC 884, but is difficult to evaluate whether this is a selection effect.

In addition to the sample described above, we also considered the two CCD $uvby\beta$ data-sets available at present for NGC 869 and NGC 884 (Marco & Bernabeu [15], Capilla & Fabregat [16]). The estimates of distance moduli and color excesses that we adopt based on these samples are shown in the second and third part of **Table 1**. Using all early-type stars in the data-set of Marco & Bernabeu [15] yields distance moduli of $11.91 (\pm 0.64$ s.d., ± 0.06 s.e.) for NGC 869 (123 stars) and $12.00 (\pm 0.36$ s.d., ± 0.04 s.e.) for NGC 884 (93 stars). For NGC 869 the majority of these stars are located between distance moduli 10.5 and 12.5. If we use only them, the average value is $11.78 (\pm 0.44$ s.d., ± 0.04 s.e.) and this is the estimate we adopt in **Table 1**. For NGC 884 the majority

of the stars are located between distance moduli 11.5 and 12.5. If we use only these stars, the average value is $12.00 (\pm 0.23$ s.d., ± 0.03 s.e.) (the one listed in **Table 1**). The data-set of Capilla & Fabregat [16] yields $DM = 11.60 (\pm 0.42$ s.d., ± 0.04 s.e.) (NGC 869, 99 stars with DM between 10.5 and 12.5 mag) and $11.71 (\pm 0.58$ s.d., ± 0.06 s.e.) (NGC 884, 91 stars with DM between 10.5 and 12.0 mag). Capilla & Fabregat [16] obtained 11.5 and 11.9 to the clusters based on cluster-fitting method. The agreement between our and their results, which are based on different methods, is very good.

It is obvious that all available $uvby\beta$ data-sets yield to the conclusion that the clusters are located at similar distances. The CCD data provide however distance moduli up to 0.75 mag larger in comparison to the photoelectric photometry. In general, the photoelectric photometry (like the one from Crawford *et al.* [14]) has been shown to be superior to CCD $uvby\beta$ photometry (see, for example, [25]). The $[c_1]$ vs. $[m_1]$ diagram, based on photoelectric data shows a much tighter main sequence in comparison to the corresponding diagrams utilizing CCD data (not shown here). In general, it is known that lower precision of the photometry can affect the accuracy of the derived stellar parameters.

Regarding the color excess, the data-set of Marco & Bernabeu [15] yields $E(b - y) = 0.44 (\pm 0.067$ s.d., ± 0.006 s.e.) and $E(b - y) = 0.40 (\pm 0.10$ s.d., ± 0.001 s.e.) for NGC 869 and NGC 884, respectively. The data-set of Capilla & Fabregat [16] provides $E(b - y)$ of 0.44 (± 0.069 s.d., ± 0.006 s.e.) (NGC 869) and 0.41 (± 0.047 s.d., ± 0.005 s.e.) (NGC 884). Within the errors, all available $uvby\beta$ data-sets lead to similar estimates of the color excess of both clusters. The estimates of the color excess do not change if stars with deviating distance moduli were excluded. We accept $E(b - y) = 0.40 (\pm 0.06$ s.d.),

Table 1. Distance moduli and color excess for NGC 869, NGC 884 and field stars (Per OB1) based on the three $uvby\beta$ data-sets available.

Quantity	NGC 869	NGC 884	Per OB1	Source of photometry
DM	$11.22 \pm 0.55 \pm 0.11$	$11.24 \pm 0.69 \pm 0.14$	$11.27 \pm 0.91 \pm 0.20$	[3]
$E(b - y)$	$0.40 \pm 0.07 \pm 0.01$	$0.40 \pm 0.05 \pm 0.01$	$0.37 \pm 0.11 \pm 0.02$	
Number of stars	24	26	21	
DM	$11.78 \pm 0.44 \pm 0.04$	$12.00 \pm 0.23 \pm 0.03$	-	[15]
$E(b - y)$	$0.44 \pm 0.03 \pm 0.003$	$0.40 \pm 0.10 \pm 0.01$	-	
Number of stars	104	66	-	
DM	$11.60 \pm 0.42 \pm 0.04$	$11.71 \pm 0.58 \pm 0.06$	-	[16]
$E(b - y)$	$0.44 \pm 0.07 \pm 0.01$	$0.41 \pm 0.05 \pm 0.01$	-	
Number of stars	99	91	-	

Note: For all estimates both the standard deviation and standard error of the mean are provided. The number of stars on which the estimates are based is shown.

corresponding to $E(B - V) = 0.54 (\pm 0.08 \text{ s.d.}) \text{ mag}$.

It is worth noting that Marco & Bernabeu [15] also provide a calculation of the average distance to the clusters based on the individual distance moduli of the B-type members. They calculate the intrinsic photometric indices adopting the average reddening for each cluster, and then for each star derive M_V from c_0 and β following Balona & Shobbrook [9] and use them to calculate the distance modulus for each cluster as the average of its members. For h Per (NGC 869), their procedure provides an average distance modulus of 11.4 ± 0.5 , while the average value for χ Per (NGC 884) is 12.1 ± 0.2 and the clusters appear to be located at slightly different distances. Our procedure is different from the one used by Marco & Bernabeu [15], since we do not use the average reddening of the clusters, but calculate the reddening for each star. It should be mentioned that the ZAMS-fitting for the data-set of Marco & Bernabeu [15] (11.66 ± 0.20 and 11.56 ± 0.20 for h Per and χ Per, respectively) provides slightly different distance moduli in comparison to the average values.

4.2. The Field of Cas OB6 Association

The relatively sparse Cas OB6 association is located towards the prominent HII regions Sh 2-190 and Sh 2-199. Humphreys [22] lists 27 O-B1 stars as members of the association, located between $l = (133^\circ, 138^\circ)$ and $b = (-0.3^\circ, 3^\circ)$ at $DM = 11.7$. Eight of these stars are members of the open cluster NGC 1805. Garmany & Stencel [23] obtained a distance modulus of 11.9 mag to the Cas OB6 association. In our sample there are 27 stars in this direction which are located significantly closer than the

previous estimates-at $DM = 8.5 (\pm 0.99 \text{ s.d.}, 0.19 \text{ s.e.})$. The stars are of relatively later spectral types (B2-B8) and apparently form a layer foreground to Cas OB6. Several very young clusters are found in this direction, IC 1805, IC 1848 and ASCC9, at DM 11.13, 11.2 and 10.97, respectively. These are the most distant and youngest clusters in our sample. They are located within several adjacent star-forming complexes (175, 176 - 180) as defined by Russeil [26]. The kinematic distances attached to these complexes show a large spread, while the distances obtained here for objects associated with the complexes are very similar.

Several other clusters with $uvby\beta$ photometry are available in the field and are listed in **Table 2**. NGC 1502 may be connected to the Cam OB1 association at $DM = 10$ (Humphreys [22]). For this cluster we obtained $DM = 9.83$. The rest of the clusters are foreground, located in a DM range of 6.6 to 10 mag.

5. Concluding Remarks

We present a $uvby\beta$ photometric investigation of a $20^\circ \times 20^\circ$ field in the second Galactic quadrant centered at coordinates $l, b = (135^\circ, 0^\circ)$. We use photoelectric data extracted from the Hauck & Mermilliod catalog [3], and also CCD data available in the literature. Our study is restricted to stars earlier than B9 spectral type. We derive the individual color excess and distance modulus for each star and then calculate the average values for the clusters and associations represented in our sample.

We estimate a distance modulus of $11.23 (\pm 0.6 \text{ s.d.}, \pm 0.12 \text{ s.e.})$, corresponding to a distance of 1762_{-95}^{+100} to h & χ Per. The layer of field stars representative for the Per

Table 2. Derived parameters for the cluster sample.

Cluster	N	l'	b'	DM (sd; se)	DM [27]	ΔDM	Age [27]	$E(b - y)$ (sd;se)
IC 1795	1	133.845	1.376	7.61::	-	-	-	0.423
IC 1805	4	134.726	0.919	11.13 (0.56; 0.28)	11.85	-0.72	6.48	0.55 (0.01; 0.01)
NGC 957	1	136.319	-2.656	9.81::	11.71	-1.90	7	0.596
IC 1848	4	136.898	1.0002	11.02 (0.90; 0.45)	11.51	-0.49	6.84	0.47 (0.02; 0.01)
ASCC9	2	137.878	-1.752	10.97:(0.44; 0.31)	12.31	-1.34	6.79	0.59 (0.03; 0.02)
NGC 1502	22	143.672	7.658	9.83 (0.38; 0.08)	10.00	-0.17	7	0.55 (0.03; 0.01)
NGC 663	27	129.467	-0.941	10.57 (0.64; 0.12)	11.92	-1.35	7.4	0.59 (0.06; 0.01)
NGC 869	24	134.632	-3.741	11.23 (0.55; 0.11)	11.59	-0.36	7.069	0.54
St 7	5	134.665	0.092	8.34 (0.40; 0.18)	9.22	-0.88	7.214	0.38 (0.01; 0.01)
NGC 884	26	135.066	-3.588	11.23 (0.69; 0.14)	12.34	-1.10	7.1	0.54
St 2	4	133.334	-1.694	6.61 (0.26; 0.13)	7.41	-0.80	8.23	0.24 (0.09; 0.04)

Note: The object's name, number of stars with $uvby\beta$ data and the galactic coordinates are given in the first four columns. The obtained here true distance moduli (together with the standard deviation and standard error of the mean provided), the distance moduli from the catalog of Dias *et al.* [27] and the difference between them are listed in columns 5, 6 and 7. The age (in log t) adopted from Dias *et al.* [27] and the color excesses obtained here are listed in the last two columns.

OB1 association is located at that same average distance. The average color excess is the same for all three groups. Evolved B-type stars are present in both clusters and among the field stars as well, but there are more numerous in NGC 869. Based on the V_0 vs. $(b - y)_0$ and M_V vs. $(b - y)_0$ diagrams one might conclude that NGC 869, NGC 884, and Per OB1 are equally old, but no quantitative comparisons to isochrones were attempted due to the relatively small sample. Apparently, a slight controversy exists between the distance modulus to h & χ Per derived based on CCD and photoelectric data. Since the photoelectric $uvby\beta$ photometry should be considered superior to CCD $uvby\beta$ photometry in terms of accuracy, preference should be given to the results based on photoelectric data.

According to our findings, the double cluster and the Per OB1 association are exactly at the same distance as the brightest members of the young groups IC 1805, IC 1848 and ASCC9. All of them are located in a $7^\circ \times 7^\circ$ area, containing the regions of intense HII emission in Sh 2-190 and Sh 2-199. IC 1805 may be part of Cas OB6 at an adopted distance modulus 11.7 (Humphreys [22]). This is an indication that the star-forming complexes associated with these objects may be also located at similar distances and clearly warrant a further investigation.

6. Acknowledgements

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