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CCD standards for U and I in the open cluster NGC 7790[⋆,⋆⋆,⋆⋆⋆]

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Abstract. Photometric U and I standard sequences in the field of the open cluster NGC 7790 are presented. The intention is to achieve wide ranges in magnitude and colour, making these sequences suitable for calibrating deep CCD photometry. The 84 standard stars extend the BVR sequences of Odewahn et al. (1992) to the near UV and IR, respectively.

Key words. techniques: photometric – astronomical data bases: miscellaneous – open clusters: individual: NGC 7790

1. Introduction

1.1. Photometric standard sequences for imaging detectors

Photometric calibration of the two-dimensional CCD detectors has to be based on standard sequences which should fulfil a number of fundamental requirements: the standard stars should cover as wide as possible a range in colour and should reach to faint magnitudes. The field of view should have the typical dimensions of a CCD field, approximately $5' \times 5'$, and the crowding of stellar images should be a minimum. Of course, the internal and external errors of magnitudes and colours should approach the limits of feasibility.

Practically all modern calibrations refer ultimately to the homogeneous photoelectrically observed set of standard stars by A. U. Landolt (1983). The underlying photometric system is often called $UBVRI$ system for simplicity. However, it relies on a combination of systems from the northern and southern hemispheres that can be summarized under the names Johnson-Kron-Cousins (for its intricate history, see Landolt 1983).

In 1985, Christian and co-workers published six photoelectric $BVRI$ standard sequences suitable for video camera and CCD calibration. They had selected between 6 and 12 stars in or near 6 clusters (M 92, NGC 2264, NGC 2419, NGC 4147, NGC 7006, and NGC 7790). Seven years later, Odewahn et al. (1992, OBH) extended three of the previous sequences (NGC 4147, NGC 7006, and NGC 7790) to fainter limits and to wider ranges in colour by means of CCD observations. However, they restricted the photometric bands to B, V, and R. A suitable U standard sequence as well as a wide standard range in I were, so far, still missing.

1.2. Standard stars in the open cluster NGC 7790

In 1995, the project "Structure of the Galaxy: evolution and kinematics of open clusters in the anticentre region" was started as a common investigation of the Universitätssternwarte Bonn, Germany, and the Institute of Astronomy of the Bulgarian Academy of Sciences, Sofia. (Details and results of the project will be given later.) For calibration purposes we used several well-known standard sequences in star clusters, e.g. in M 67 (Montgomery et al. 1993), and in M 92 (Majewski et al. 1994), but most of our photometry was calibrated with standard stars in the open cluster NGC 7790.

The coordinates of NGC 7790 are RA = $23^{\rm h}58\overset{\rm m}{.}4$ and Dec = $+61°13'$ (2000). Therefore, most of the year it can be observed from northern sky observatories. Being an intermediate-age open cluster (approx. 120 Myr, Gupta et al. 2000), it is suitable for calibration of different types of astronomical objects, like clusters and distant galaxies.

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⋆ Based on observations collected at the National Astronomical Observatory Rozhen, Bulgaria.

⋆⋆ This work is part of a common project between the Universitätssternwarte Bonn, Germany, and the Institute of Astronomy of the Bulgarian Academy of Sciences to study binary open star clusters and clusters in the direction of the Galactic anticentre.

⋆⋆⋆ Full Table 4 is only available in electronic form at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via
http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/376/745

Table 1. Observational data for NGC 7790 from the 2 m RC telescope.

date	filter	No. of frames per filter	scale [″/px]	seeing [″]
1998-02-28	U, B, V, R, I	2	0.62	≤2
1998-08-23	U, B, V, R, I	4	0.62	1.5 ... 2
1998-08-23	U, B, V, R, I	2	0.31	1.5 ... 2
1998-09-06	U, B, V, R, I	10	0.62	2.5 ... 3

The basic sample of our U and I calibration is a list of 13 stars ("primary standards") in NGC 7790 with observed magnitudes in the passband U which refer to the fundamental standards of Landolt (1983); see Sect. 3. This list is enlarged to a total of 84 stars which are in common with the improved BVR standards from OBH (1992); see Sect. 5. The ranges in magnitudes and colours are, e.g., $13.15 < V < 18.52$, $0.39 < B-V < 1.71$, and $0.25 < V-R < 1.28$ (always given in mag). The stars are spread over a field of view of $5' \times 3'.5$ to the south-east of the cluster's centre.

We note for the sake of completeness only that Schmidt (1981) published Strömgren photometry of stars in NGC 7790. Recently Stetson (2000) published Landolt calibrated $BVRI$ data for about 240 stars in a field of $6' \times 6'$ centred on NGC 7790.

2. Observations and data reduction

The basic observational data for NGC 7790 are presented in Table 1. These frames have been taken with the "Photometrics" CCD camera at the 2 m RC telescope of Rozhen observatory. The detector SITE SI003AB has 1024×1024 px, with a pixel size of $24 \times 24\,\mu^2$. Two regimes of observations are at disposal to the observer: (1) Gain = 4.93, RON = 1.05 ADUs and (2) Gain = 1.21, RON = 2.73 ADUs. The scale is $0''.31$/px without binning and $0''.62$/px with binning. At the RC focus of the 2 m telescope the field of view is $5' \times 5'$. The filter system is close to Johnson's UBV (including a read-leak suppression filter), and Kron/Cousins' RI:
U: 2 mm UG1 + 1 mm BG39;
B: 1 mm BG14 + 1 mm GG1 + 1 mm BG23;
V: 2 mm GG495 + 1 mm GG11;
R: 1 mm OG570 + 1 mm KG3;
I: 3 mm RG9. After standard image reduction with MIDAS, profile fitting photometry was carried out with DAOPHOT II (Stetson 1991) running under MIDAS.

3. Constructing the U and I standard sequences

Unfortunately, there are no suitable standard stars for U in NGC 7790. The only available U data come from
– Sandage (1958): 22 stars, most of them with one single photoelectric observation only;
– Alcalá & Arellano Ferro (1988, AAF): re-observation of 16 stars from Sandage's list with reference to the Landolt standards;
– Pedreros et al. (1984, PMF): photographic observations calibrated by Sandage's U sequence which they had corrected by 0.075 mag due to an apparent offset in the U scale (Sandage's observations are too blue).

The stars of these lists are spread over an area of about $10' \times 10'$ around the centre of the cluster. The dynamical interval of these data – in magnitudes and colours – is not large enough for CCD receivers and improved techniques of data reduction.

From these lists we find 4 AAF stars and 9 PMF stars (from the corrected Sandage sequence) which coincide with BVR standard stars from OBH. We chose these 13 stars as primary standards in the passband U. They are listed in Table 2 with their OBH numbers; the first 4 stars are those from AAF, the following 9 from PMF. Note that we did not use star no. OBH-31 (= AAF-36), because this star has an elliptical shape and is always rejected automatically in the reduction process.

We used the same 13 stars to construct our primary standard sequence in the passband I. The first 4 stars (see Table 2) have I magnitudes from the CCD work of Romeo et al. (1989). For the remaining stars we can refer to the basic sequence of Christian et al. (1985).

4. Methods of calibration

For the final calibration we used a three-step iteration method for the following reason: (1) The $UBVRI$ data of the 13 primary standards are taken from different sources with different reliability. The aim of the process is to homogenize the mixed sample and to minimize the influence of bright primary stars determined with lower accuracy. (2) The original sequence covers only a narrow interval of colours and the distribution in magnitude is rather nonuniform. The iteration allows us to enlarge the interval of magnitudes and colours of the standards.

Photometric transformation coefficients were determined in three steps using the following transformation relations:

$$U_{\rm st} = a_{0U} + a_{1U} \cdot U_{\rm in} + a_{2U} \cdot (U_{\rm in} - B_{\rm in}) \quad (1)$$

$$I_{\rm st} = a_{0I} + a_{1I} \cdot I_{\rm in} + a_{2I} \cdot (R_{\rm in} - I_{\rm in}) \quad (2)$$

where $M_{\rm st}$ are the photometrically calibrated magnitudes and $M_{\rm in}$ are the instrumental ones. As the standards and the programme stars are located in the same field, no extinction correction is needed (see e.g. Hardie 1962; Strayzis 1977).

• Step (1): Determine the transformation coefficients using the above 13 stars discussed and compute the First Step Standard Magnitudes (FSSM) for all the objects in the field of interest.

• Step (2): Use an enlarged standard sequence of 25 stars – 12 more stars added to the first 13 primaries with the FSSM (step 1) – and recompute the magnitudes of all stars in the field, in this way getting the Second Step

Table 2. U and I magnitudes of the 13 primary standard stars and comparison with the calibration via the cluster M 92. (All values are given in mag.) For details of notation see text.

No.	U_s	$\sigma(U_s)$	I_s	$\sigma(I_s)$	$U_{M\,92}$	$d(U)$	$I_{M\,92}$	$d(I)$
29	13.611	0.0110	12.782	0.0042	13.622	−0.011	12.789	−0.007
30	13.838	0.0110	12.929	0.0046	13.868	−0.030	12.935	−0.007
36	15.063	0.0090	13.917	0.0300	15.116	−0.053	13.936	−0.019
37	15.330	0.0152	14.149	0.0060	15.308	+0.021	14.142	+0.007
51	14.903	0.0131	13.865	0.0064	14.882	+0.021	13.840	+0.025
58	16.358	0.0156	14.724	0.0159	16.363	−0.005	14.754	−0.030
59	16.895	0.0150	15.302	0.0104	16.871	+0.025	15.298	+0.003
62	18.277	0.0247	13.500	0.0260	18.318	−0.041	13.488	+0.013
65	17.079	0.0121	15.080	0.0185	17.147	−0.068	15.097	−0.017
72	14.541	0.0170	13.521	0.0064	14.521	+0.020	13.513	+0.008
77	17.020	0.0142	15.074	0.0092	17.025	−0.005	15.043	+0.031
88	17.178	0.0159	14.649	0.0078	17.090	+0.088	14.654	−0.005
97	15.924	0.0406	11.593	0.0131	15.886	+0.038	11.595	−0.002

Standard Magnitudes (SSSM). We note that the choice of these 12 additional stars is somewhat arbitrary. Attempts with 10 to 15 stars showed us that it should be an appropriate number of faint stars with small photometric errors and spread over the whole field.

• Step (3): Repeat step 2 for *all* stars with the magnitudes of the 25 "new" standards from the SSSM and compute the Third Step Standard Magnitudes (TSSM) of *all the stars* in the field. Now, the relative change of the coefficients in Eqs. (1) and (2) is 0.005 for a_{2U} and less than 0.0005 for all other coefficients. Furthermore, controlling the differences between SSSM and FSSM, and TSSM and SSSM, our results are internally consistent that no further iteration is needed.

An additional check of the quality of our calibration was performed by recalibrating our 13 primary stars using the standard sequence in M 92 (see the following section).

5. Results

The U and I magnitudes of our 13 primary standard stars are given in Table 2 and are denoted U_s and I_s. The standard errors $\sigma(U_s)$ and $\sigma(I_s)$ of the individual magnitudes are also listed. They are the result of the whole process of reduction and calibration. The mean value is $<\sigma> = 0.0165$ mag in U and $<\sigma> = 0.0122$ mag in I. The larger error in U reflects the fact that the CCD receivers are less sensitive in the ultraviolet, which means a smaller signal-to-noise-ratio for the observed stars; apart from photon statistics, no other source of noise is significant.

As mentioned above, we applied an independent calibration of our 13 primary stars using the standard sequence in the globular cluster M 92 established by Majewski et al. (1994): after extinction correction of the instrumental magnitudes, we carried out the photometric calibration in the form

$$U_{M\,92} = c_U + c'_U \cdot U_{ec} + c''_U \cdot (U_{ec} - B_{ec}) \quad (3)$$

$$I_{M\,92} = c_I + c'_I \cdot I_{ec} + c''_I \cdot (R_{ec} - I_{ec}) \quad (4)$$

where $M_{M\,92}$ are the standard magnitudes after photometric calibration via M 92 and M_{ec} are the extinction-corrected instrumental magnitudes. The magnitudes $U_{M\,92}$ and $I_{M\,92}$ are displayed in Cols. 6 and 8 of Table 2. The quality of our calibration process is immediately apparent: The sums of the differences $d(U)$ and $d(I)$ to our basic calibration (again Table 2, Cols. 7 and 9) are in both cases exactly 0.000 mag. Therefore no shift in magnitude between the different methods of calibrations can be seen. The mean differences (positive or negative) between the magnitudes of the two calibrations are small: 0.033 mag in U and 0.013 mag in I, respectively.

The NGC 7790 field of OBH is not completely identical to our field because they chose the south eastern part of the cluster whereas we centred our frames onto the clusters centre. In addition, not all OBH stars have measurable U values due to the lower sensitivity of the CCD in this passband. As a result, in the overlapping section there are 84 stars for which the complete $UBVRI$ data set is now available. The $UBVRI$ magnitudes and their errors for all these stars are listed in Table 4 with their OBH numbers. We have chosen the notation U_s, B_s etc. The photometric errors of the individual stellar magnitudes after DAOPHOT photometry have been added. The last three columns of the table display the differences between the magnitudes BVR from our work and those from the OBH sequence.

We have plotted the errors versus the calibrated magnitudes for all passbands in Fig. 1. The means $<\sigma>$ of the individual errors can be read off Table 3. As expected, the mean error in the U band is fairly large: $<\sigma> = 0.032$ mag. The individual errors become

Table 3. Magnitude intervals and mean errors for the standard sequences in NGC 7790, and summary of the comparison. (All values are given in mag.)

	This paper		Odewahn et al. (1992)		Difference d	
Filter	range	$< \sigma >$	range	$< \sigma >$	shift	$<\|d\|>$
U	13.61 ... 20.01	0.032				
B	13.61 ... 19.54	0.009	13.64 ... 19.67	0.024	−0.002	0.049
V	13.14 ... 18.48	0.009	13.15 ... 18.52	0.014	−0.002	0.047
R	12.35 ... 17.88	0.017	12.37 ... 17.92	0.021	+0.002	0.059
I	11.59 ... 19.67	0.015				

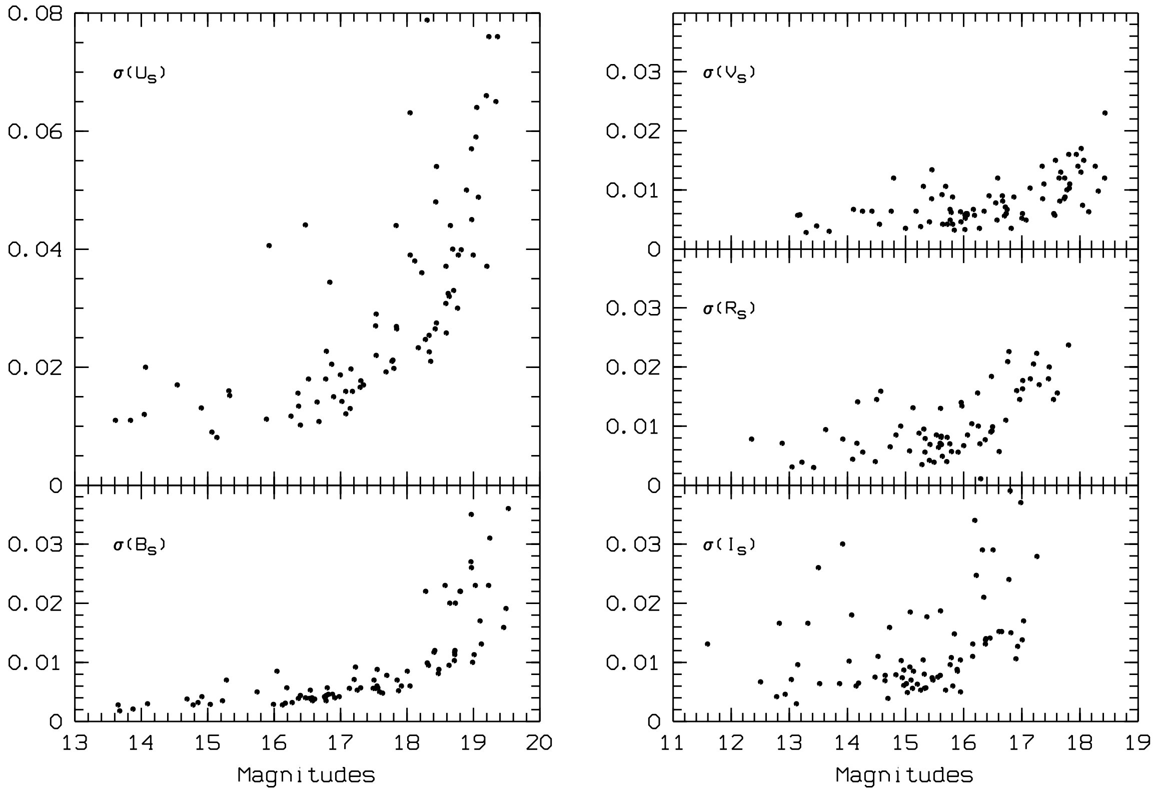

Fig. 1. Errors of the photometric calibration vs. standard star magnitudes.

large above $U = 19$ mag, but still are quite small for magnitudes below $U = 18$ mag (see Fig. 1). With only few exceptions, the individual errors in B and V are less than 0.03 mag below 19 mag. For the R band the errors are as usual quite small – less than 0.02 mag for all magnitude intervals – except for a group of 7 stars between 17 to 18 mag which show errors of about 0.05–0.06 mag (outside the frame of Fig. 1). This might be due to the effect of severe crowding because the R fields are quite rich in stars. The errors from the I frames are fully acceptable; they are less than 0.04 mag below $I = 16$ mag. There are unexpected large photometric errors for stars Nos. 21, 48, and 97 in U (see Fig. 1, upper left panel). Careful inspection of the original frames shows no reason for such errors: the three stars are isolated, comparatively bright, and far from the edges of the frames. Nevertheless, we did not remove the stars from our list so that the larger errors are a warning for possible users.

The errors of the colours have been computed following the rules of error propagation. As expected from Fig. 1, these errors increase with increasing magnitudes. No other tendency is apparent.

Finally, we compare our results with those of OBH. The ranges in the magnitudes BVR and the means of the individual errors are compared in the first two sections of Table 3. The errors of our work are marginally smaller, but, in principle, the results are quite similar. The differences $d(B) = B_{\rm s} - B_{\rm od}$; $d(V) = V_{\rm s} - V_{\rm od}$; and $d(R) = R_{\rm s} - R_{\rm od}$, in the sense "our magnitude minus OBH's magnitude", are listed in the last columns of Table 4. The differences have been plotted in Fig. 2 vs. the magnitudes from this paper. No systematic difference between the two calibrations can be seen. Indeed, the mean deviations from

Table 4. Magnitudes and errors of all 84 standard stars. The first column refers to the notation of Odewahn et al. (1992). The last three columns give the difference between the listed magnitudes and those from the BVR sequence of Odewahn et al.'s (1992) paper. (All values are given in mag.) The complete table is availabale only in electronic form at the CDS archive, `cdsarc.u-strasbg.fr (130.79.128.5)` or via `http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/376/745`

No.	U_s	$\sigma(U_s)$	B_s	$\sigma(B_s)$	V_s	$\sigma(V_s)$	R_s	$\sigma(R_s)$	I_s	$\sigma(I_s)$	$d(B)$	$d(V)$	$d(R)$
8	17.144	0.0130	16.912	0.0040	16.270	0.0035	15.904	0.0056	15.471	0.0070	−0.057	−0.038	−0.010
9	18.170	0.0233	18.045	0.0060	17.073	0.0049	16.497	0.0099	15.887	0.0088	−0.080	−0.047	−0.031
10	18.332	0.0254	18.479	0.0088	17.550	0.0060	16.963	0.0145	16.373	0.0131	−0.026	−0.027	−0.066
11	18.222	0.0360	17.916	0.0060	17.011	0.0060	16.466	0.0090	15.945	0.0050	+0.059	+0.018	+0.012
12	18.761	0.0300	19.010	0.0113	18.045	0.0074	17.458	0.0180	16.899	0.0106	−0.024	−0.024	+0.003
16	16.776	0.0180	16.544	0.0053	15.946	0.0063	15.610	0.0081	15.203	0.0063	+0.012	+0.005	+0.007
17	16.395	0.0102	16.168	0.0031	15.638	0.0042	15.333	0.0056	14.969	0.0061	−0.081	−0.094	−0.110
18	19.074	0.0488	19.119	0.0131	18.151	0.0063	17.545	0.0145	16.928	0.0127	−0.427	−0.181	−0.157
20	16.517	0.0180	16.271	0.0032	15.717	0.0042	15.409	0.0042	15.031	0.0049	+0.027	+0.021	+0.029
21	16.838	0.0344	16.577	0.0035	16.020	0.0033	15.709	0.0040	15.324	0.0056	−0.003	−0.009	−0.031
22	18.335	0.0226	17.204	0.0071	15.767	0.0049	14.916	0.0100	14.029	0.0102	−0.012	+0.000	+0.008
23	17.536	0.0290	16.569	0.0040	14.999	0.0035	14.090	0.0044	13.035	0.0071	+0.003	+0.002	+0.007
24	17.344	0.0170	17.250	0.0053	16.573	0.0049	16.610	0.0057	15.688	0.0053	−0.038	−0.049	+0.365
25	16.996	0.0187	16.781	0.0035	15.838	0.0032	15.282	0.0035	14.696	0.0039	+0.018	+0.047	+0.034
26	17.536	0.0220	17.503	0.0070	16.731	0.0060	16.279	0.0070	15.812	0.0060	−0.017	+0.016	+0.012
27	18.424	0.0265	18.471	0.0081	17.568	0.0057	17.016	0.0177	16.453	0.0141	−0.028	−0.007	−0.036
28	17.840	0.0269	17.587	0.0050	16.817	0.0035	16.370	0.0077	15.892	0.0085	−0.096	−0.102	−0.115
29	13.611	0.0110	13.675	0.0018	13.289	0.0028	13.047	0.0031	12.782	0.0042	−0.021	−0.016	−0.010
30	13.838	0.0110	13.875	0.0021	13.470	0.0039	13.217	0.0039	12.929	0.0046	+0.095	+0.097	+0.094
31	14.064	0.0200	14.094	0.0030	13.685	0.0030	13.419	0.0030	13.122	0.0030	+0.052	+0.088	+0.109
32	16.253	0.0117	15.990	0.0029	15.410	0.0046	15.069	0.0058	14.646	0.0069	−0.006	+0.008	+0.020
34	18.635	0.0320	18.632	0.0095	17.743	0.0088	17.201	0.0205	16.652	0.0152	+0.010	+0.019	+0.031
35	18.996	0.0390	19.490	0.0191	18.315	0.0098	17.610	0.0156	17.007	0.0138	+0.113	−0.076	−0.101
36	15.063	0.0090	15.038	0.0029	14.551	0.0042	14.263	0.0056	13.917	0.0300	+0.027	+0.025	+0.036
37	15.330	0.0152	15.222	0.0035	14.753	0.0064	14.479	0.0040	14.149	0.0060	+0.031	+0.029	+0.037
38	17.077	0.0159	16.816	0.0046	16.186	0.0057	15.790	0.0057	15.348	0.0057	+0.037	+0.054	+0.032
39	18.970	0.0570	18.728	0.0200	17.640	0.0120	16.980	0.0480	16.191	0.0340	−0.063	+0.018	+0.020
40	19.362	0.0760	18.970	0.0260	17.776	0.0100	17.067	0.0420	16.264	0.0630	+0.013	+0.036	+0.053
41	18.772	0.0390	18.643	0.0200	17.737	0.0120	17.193	0.0580	16.593	0.0490	+0.042	+0.028	+0.010
42	19.194	0.0660	18.967	0.0350	17.930	0.0440	17.351	0.0670	16.760	0.0410	+0.249	+0.341	+0.431
43	19.202	0.0371	19.455	0.0159	18.424	0.0120	17.803	0.0237	17.260	0.0279	+0.122	+0.107	+0.089
45	16.646	0.0141	16.365	0.0039	15.809	0.0042	15.490	0.0039	15.119	0.0056	+0.026	+0.031	+0.024
48	16.470	0.0441	16.124	0.0028	15.259	0.0038	14.735	0.0065	14.191	0.0065	+0.006	−0.002	−0.007
49	18.895	0.0500	18.280	0.0220	16.585	0.0120	15.601	0.0130	14.526	0.0110	+0.020	+0.012	+0.036
51	14.903	0.0131	14.854	0.0032	14.421	0.0064	14.163	0.0071	13.865	0.0064	+0.005	−0.009	−0.016
53	17.305	0.0177	16.978	0.0042	16.351	0.0064	16.000	0.0067	15.597	0.0078	+0.029	+0.028	+0.020
54	17.773	0.0210	17.560	0.0057	16.551	0.0078	15.969	0.0134	15.366	0.0177	−0.002	−0.008	+0.022
55	18.653	0.0440	18.987	0.0100	18.021	0.0170	17.471	0.0200	17.030	0.0170	+0.053	+0.072	+0.085

the zero-axes are only 0.05 mag (see also the last column of Table 3; only star No. 106, which has the extremely large difference of 0.5 mag in all three bands, has been omitted from the calculation).

The sum of all differences in each passband gives the shift in magnitude between the two standard sequences. It is apparent from Table 3 (right section) that the shifts are only two thousandths of a magnitude.

We conclude that our calibration of the standard sequence in the NGC 7790 field perfectly agrees with OBH's calibration for the bands B, V, and R, and we, therefore, have an additional strong indication that our calibrations for the bands U and I are in good state, too.

6. Concluding remarks

We have constructed a primary standard sequence of 13 stars in U and I in the field of the open cluster NGC 7790. With these standards we were able to extend the B, V, and R sequences of OBH to the bands U and I. These new standard sequences contain 84 stars over wide ranges of magnitude and colour.

We emphasize that three factors support the reliability of the new U and I sequences:

• We applied a three-step iteration method which integrates additional stars into the process of calibration. This leads to higher accuracy for a sample of stars covering wider intervals of magnitude and colour.

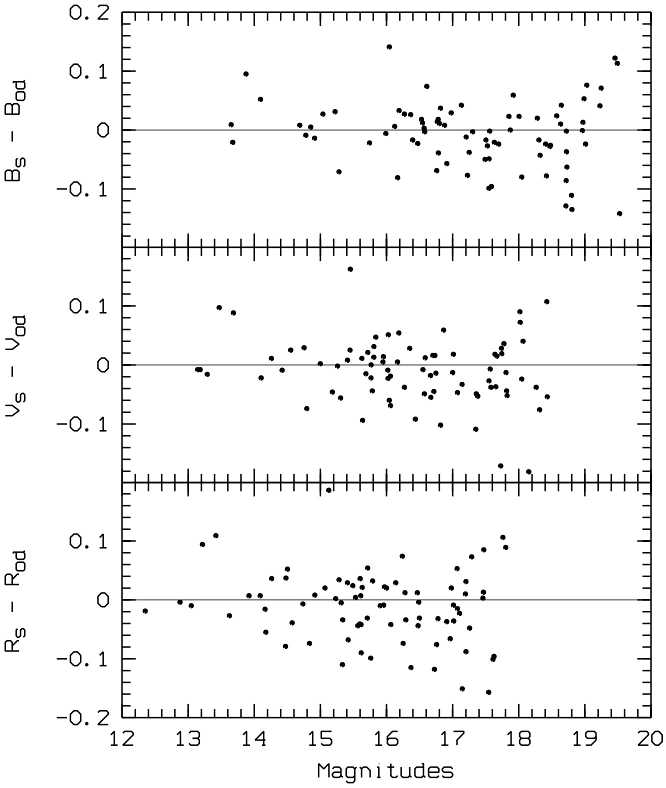

Fig. 2. Comparison of our calibrated BVR magnitudes with the corresponding magnitudes of Odewahn et al. (1992).

• We applied an independent calibration to our 13 primary standard stars using the standard sequence in the globular cluster M 92 (Majewski et al. 1994). The results of both calibrations agree very well with each other (see Table 2).
• A comparison of our BVR results with those of OBH for the 84 stars in common again gives perfect agreement.

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