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On linear fit to ZAMS and reddening determination

Ulisse Munari[1] and Giovanni Carraro[2]

[1] Osservatorio Astronomico di Padova, Sede di Asiago, I-36012 Asiago (VI), Italy (munari@astras.pd.astro.it)
[2] Dipartimento di Astronomia, Universita di Padova, Vicolo dell'Osservatorio, I-35100 Padova, Italy (carraro@astrpd.pd.astro.it)

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Abstract. We re-discuss in detail the use of linear fit to the $(B-V),(B-I)$ ZAMS of open clusters proposed by Natali et al. (1994) to measure the reddening. A proper link to the Cousins photometric system and evaluation of the adopted extinction law shows that the application of the proposed method must be carefully handled over observational data to avoid large errors. Other combinations of colors are explored in search for a higher sensitivity to reddening, which in any case remains quite poor.

Key words: dust: extinction – open clusters – techniques: photometric

1. Introduction

Natali et al. (1994, hereafter NNPP94) have recently suggested the use of $(B-V),(B-I)$ color relation to estimate interstellar reddening for open clusters. The I band used by NNPP94 is on the Johnson's system (1965, and therein references). NNPP94 suggested that the ZAMS on the $(B-V),(B-I)$ plane is a straight line over the entire observed $(B-V)$ range (up to 3.5). Departures from a linear relation are however visible in the data NNPP94 reported for the clusters they investigated. The departure of ZAMS from a linear relation is also apparent in the original calibration of the photometric system by Johnson (1966).

Due to difficulties in reproducing the original photometric system and lack of standard stars, the Johnson's I band has been generally replaced by the one in the Cousins' system, for which a larger and highly consistent set of standard stars are available in the southern E-regions and equatorial Landolt's fields.

In this note we review the NNPP94 method to determine the reddening of open clusters from linear fits to the ZAMS. The application to the $(B-V),(B-I)$ plane is re-discussed and other color combinations in the Cousins UBVR$_C$I$_C$ system are evaluated.

2. Method

The idea is to search for a linear relation between color indexes and to calibrate a simple reddening relation in term of linear fit to the observed data.

Send offprint requests to: U. Munari

Table 1. $\frac{A(\lambda)}{A(J)}$ for UBVR$_C$I$_C$R$_J$I$_J$ bands when R$_V$=3.1 and R$_V$=5.0

R_V	$\frac{A(U)}{A(J)}$	$\frac{A(B)}{A(J)}$	$\frac{A(V)}{A(J)}$	$\frac{A(R_C)}{A(J)}$	$\frac{A(I_C)}{A(J)}$	$\frac{A(R_J)}{A(J)}$	$\frac{A(I_J)}{A(J)}$
3.1	5.53	4.65	3.58	3.00	2.23	2.70	1.84
5.0	4.06	3.64	3.07	2.68	2.10	2.46	1.80

Denoting the photometric bands with W_i, we are looking for the existence (over a given range $\epsilon_1 \leq (W_1-W_2)_\circ \leq \epsilon_2$ of applicability) of a relation of the type

$$(W_3-W_4)_\circ = \alpha + \beta \times (W_1-W_2)_\circ \qquad (1)$$

Ignoring effects linked to shift of effective wavelength with spectral types, for a given extinction law it is

$$\frac{E_{(W_3-W_4)}}{E_{(W_1-W_2)}} = \gamma \qquad (2)$$

and therefore Eq. (1) can be re-written in term of observed quantities as

$$(W_3-W_4) = \alpha + \beta \times (W_1-W_2) + (\gamma-\beta) \times E_{(W_1-W_2)} \qquad (3)$$

In a (W_1-W_2),(W_3-W_4) color plot, the data corresponding to the range of relation validity ϵ_1, ϵ_2 must be fitted with a first order polinomial of β slope. The zero order term produced by the fitting is therefore

$$Q = \alpha + (\gamma-\beta) \times E_{(W_1-W_2)} \qquad (4)$$

which can be re-written as

$$E_{(W_1-W_2)} = \frac{Q-\alpha}{\gamma-\beta} \qquad (5)$$

The larger $\gamma-\beta$, the greater the method sensitivity because for a given color excess the displacement Q of the linear fit increases. For a vanishing $\gamma-\beta$, the reddening simply produces a shift of the data *along* the locus given by Eq. (1) and no color excess can be measured.

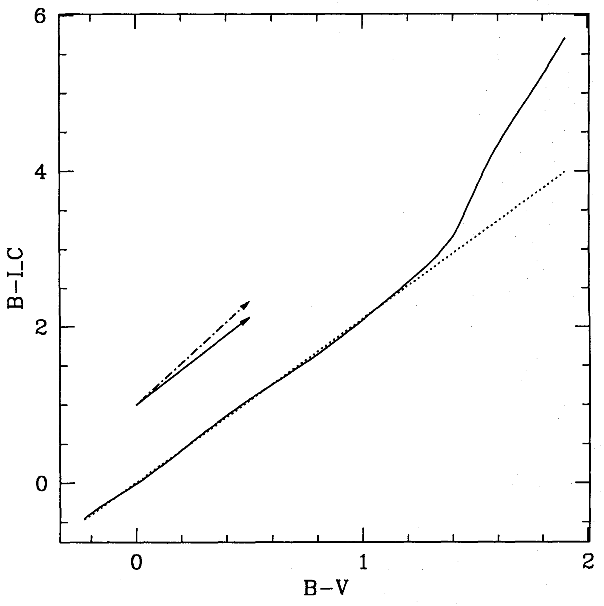

Fig. 1. The ZAMS and linear fit on the $(B-V),(B-I_C)$ plane. The solid and dashed arrows show the reddening vector for the R_V=3.1 and R_V=5.0 laws, respectively.

3. Reddening relations in the (B-V),(B-I) plane

NNPP94 suggested the existence of linear relations of the type (1) for various color combinations when examining published photometry of open clusters. They reported reasons to prefer the $(B-V),(B-I)$ one and adopted the reddening relation given by Rieke & Lebofski (1985)

$$\frac{E_{(B-I_J)}}{E_{(B-V)}} = 2.64$$

The extensive review on interstellar extinction presented by Mathis (1990, hereafter M 90) shows how different extinction laws exist in the astronomical environments where open clusters are found. The M 90 relation for $R_V = A(V)/E_{(B-V)} = 3.1$ applies to the general galactic field (with some restrictions), the one for $R_V = 5.0$ better represents the conditions in the outer regions of molecular clouds were young open clusters are frequently observed. To derive the extinction coefficients in the $UBVR_CI_C + R_JI_J$ system, we have weighted the two M 90 laws over the bands profiles, taken from Lamla (1982; Vilnius Observatory reconstruction) for U and B, Bessell (1976) for V, R_C and I_C and Johnson (1965) for R_J and I_J. The results are given in Table 1. Assuming a flat stellar energy distribution, we have further derived the relations presented in Table 2 between color excesses. For the Cousins and Johnson photometric systems, the reddening relations in the $(B-V),(B-I)$ plane are

$$\frac{E_{(B-I_C)}}{E_{(B-V)}} = 2.25 \qquad \text{[for the R}_V = 3.1\text{ law]} \tag{6}$$

$$\frac{E_{(B-I_C)}}{E_{(B-V)}} = 2.66 \qquad \text{[for the R}_V = 5.0\text{ law]} \tag{7}$$

$$\frac{E_{(B-I_J)}}{E_{(B-V)}} = 2.62 \qquad \text{[for the R}_V = 3.1\text{ law]} \tag{8}$$

$$\frac{E_{(B-I_J)}}{E_{(B-V)}} = 3.19 \qquad \text{[for the R}_V = 5.0\text{ law]} \tag{9}$$

4. ZAMS on the (B–V)/(B–I$_C$) plane

An accurate definition of the ZAMS locus on the $(B-V),(B-I_C)$ plane for Population I stars can be derived from the numerical expressions given by Caldwell et al. (1993), who discussed the extensive observational data gathered at the South African Astronomical Observatory by A.W.J.Cousins and collaborators in the last decades. The computed ZAMS is presented in Table 3 and Fig. 1. It is quite obvious that it cannot be represented by a linear relation over its entire extension.

The ZAMS in Table 3 can be roughly fitted with the linear relation

$$(B-I_C)_\circ = +0.014 + 2.091 \times (B-V)_\circ \tag{10}$$

over the range $-0.23 \leq (B-V)_\circ \leq +1.30$. In this case Eq. (5) becomes

$$E_{(B-V)} = \frac{Q-0.014}{0.159} \qquad \text{[for the R}_V = 3.1\text{ law]} \tag{11}$$

$$E_{(B-V)} = \frac{Q-0.014}{0.569} \qquad \text{[for the R}_V = 5.0\text{ law]} \tag{12}$$

The corresponding relations obtained by NNPP94 are

$$(B-I_J)_\circ = 2.36 \times (B-V)_\circ$$

$$E_{(B-V)} = \frac{Q}{0.28}$$

without imposed restrictions on the $(B-V)_\circ$ range of applicability. In the Johnson (1965) system, the relations are (range of applicability $-0.32 \leq (B-V)_\circ \leq +1.30$)

$$(B-I_J)_\circ = +0.013 + 2.407 \times (B-V)_\circ \tag{13}$$

$$E_{(B-V)} = \frac{Q-0.013}{0.212} \qquad \text{[for the R}_V = 3.1\text{ law]} \tag{14}$$

$$E_{(B-V)} = \frac{Q-0.013}{0.784} \qquad \text{[for the R}_V = 5.0\text{ law]} \tag{15}$$

once the M 90 extinxtion laws are adopted and the original Johnson (1966) data for Population I ZAMS are used in the computations instead of published photometry of open clusters.

However, close inspection of Fig. 1 and Table 3 shows that the real ZAMS well fluctuate around the linear fit given in Eq. (10). A more satisfactory approximation of the ZAMS is achievable with a set of four linear fits over sub-intervals of the $-0.32 \leq (B-V)_\circ \leq +1.30$ range where Eq. (10) applies:

$$(B-I_C)_\circ = -0.003 + 1.882 \times (B-V)_\circ \tag{16}$$
$$\text{[for } -0.23 \leq (B-V)_\circ \leq +0.05]$$

$$(B-I_C)_\circ = -0.019 + 2.250 \times (B-V)_\circ \tag{17}$$
$$\text{[for } +0.05 \leq (B-V)_\circ \leq +0.40]$$

$$(B-I_C)_\circ = +0.118 + 1.911 \times (B-V)_\circ \tag{18}$$

Table 2. Color excess relations for R_V=3.1 and R_V=5.0 in the Cousins system

	$E_{(U-B)}$	$E_{(U-V)}$	$E_{(U-R_C)}$	$E_{(U-I_C)}$	$E_{(B-V)}$	$E_{(B-R_C)}$	$E_{(B-I_C)}$	$E_{(V-R_C)}$	$E_{(V-I_C)}$	$E_{(R_C-I_C)}$
					R_C=3.1					
$E_{(U-B)}$	1.00	2.22	2.87	3.74	1.22	1.87	2.74	0.66	1.52	0.87
$E_{(U-V)}$	0.45	1.00	1.30	1.69	0.55	0.84	1.24	0.30	0.69	0.39
$E_{(U-R_C)}$	0.35	0.77	1.00	1.30	0.42	0.65	0.95	0.23	0.53	0.30
$E_{(U-I_C)}$	0.27	0.59	0.77	1.00	0.33	0.50	0.73	0.18	0.41	0.23
$E_{(B-V)}$	0.82	1.82	2.36	3.08	1.00	1.54	2.25	0.54	1.25	0.71
$E_{(B-R_C)}$	0.53	1.18	1.53	2.00	0.65	1.00	1.47	0.35	0.81	0.46
$E_{(B-I_C)}$	0.37	0.81	1.05	1.37	0.44	0.68	1.00	0.24	0.56	0.32
$E_{(V-R_C)}$	1.52	3.37	4.37	5.69	1.85	2.85	4.17	1.00	2.31	1.32
$E_{(V-I_C)}$	0.66	1.46	1.89	2.46	0.80	1.23	1.80	0.43	1.00	0.57
$E_{(R_C-I_C)}$	1.15	2.56	3.32	4.32	1.40	2.16	3.16	0.76	1.76	1.00
					R_C=5.0					
$E_{(U-B)}$	1.00	2.40	3.33	4.73	1.40	2.33	3.73	0.93	2.33	1.39
$E_{(U-V)}$	0.42	1.00	1.39	1.97	0.58	0.97	1.55	0.39	0.97	0.58
$E_{(U-R_C)}$	0.30	0.72	1.00	1.42	0.42	0.70	1.12	0.28	0.70	0.42
$E_{(U-I_C)}$	0.21	0.51	0.71	1.00	0.30	0.49	0.79	0.20	0.49	0.29
$E_{(B-V)}$	0.71	1.71	2.38	3.38	1.00	1.67	2.66	0.67	1.66	1.00
$E_{(B-R_C)}$	0.42	1.03	1.43	2.03	0.60	1.00	1.60	0.40	1.00	0.60
$E_{(B-I_C)}$	0.27	0.64	0.89	1.27	0.38	0.63	1.00	0.25	0.62	0.37
$E_{(V-R_C)}$	1.07	2.57	3.57	5.06	1.50	2.50	4.00	1.00	2.49	1.49
$E_{(V-I_C)}$	0.43	1.03	1.43	2.03	0.60	1.00	1.60	0.40	1.00	0.60
$E_{(R_C-I_C)}$	0.72	1.72	2.39	3.39	1.00	1.67	2.67	0.67	1.67	1.00

Table 3. The ZAMS for Population I stars in the $(B-V)$,$(B-I_C)$ plane.

$(B-V)_o$	$(B-I_C)_o$	$(B-V)_o$	$(B-I_C)_o$	$(B-V)_o$	$(B-I_C)_o$	$(B-V)_o$	$(B-I_C)_o$	$(B-V)_o$	$(B-I_C)_o$	$(B-V)_o$	$(B-I_C)_o$
-0.220	-0.427	0.140	0.294	0.500	1.075	0.860	1.776	1.220	2.615	1.580	4.231
-0.200	-0.381	0.160	0.339	0.520	1.113	0.880	1.819	1.240	2.665	1.600	4.333
-0.180	-0.339	0.180	0.384	0.540	1.152	0.900	1.863	1.260	2.716	1.620	4.430
-0.160	-0.300	0.200	0.430	0.560	1.190	0.920	1.907	1.280	2.769	1.640	4.522
-0.140	-0.263	0.220	0.476	0.580	1.227	0.940	1.952	1.300	2.824	1.660	4.612
-0.120	-0.226	0.240	0.521	0.600	1.265	0.960	1.997	1.320	2.882	1.680	4.699
-0.100	-0.190	0.260	0.567	0.620	1.303	0.980	2.043	1.340	2.943	1.700	4.786
-0.080	-0.154	0.280	0.612	0.640	1.340	1.000	2.089	1.360	3.008	1.720	4.874
-0.060	-0.117	0.300	0.657	0.660	1.378	1.020	2.136	1.380	3.078	1.740	4.961
-0.040	-0.080	0.320	0.702	0.680	1.416	1.040	2.182	1.400	3.153	1.760	5.052
-0.020	-0.042	0.340	0.745	0.700	1.454	1.060	2.230	1.420	3.258	1.780	5.143
0.000	-0.036	0.360	0.789	0.720	1.492	1.080	2.277	1.440	3.376	1.800	5.236
0.020	0.036	0.380	0.832	0.740	1.531	1.100	2.324	1.460	3.502	1.820	5.330
0.040	0.077	0.400	0.874	0.760	1.570	1.120	2.372	1.480	3.631	1.840	5.424
0.060	0.119	0.420	0.915	0.780	1.610	1.140	2.420	1.500	3.760	1.860	5.519
0.080	0.161	0.440	0.956	0.800	1.651	1.160	2.468	1.520	3.886	1.880	5.614
0.100	0.205	0.460	0.996	0.820	1.692	1.180	2.516	1.540	4.007	1.900	5.708
0.120	0.249	0.480	1.036	0.840	1.734	1.200	2.565	1.560	4.122		

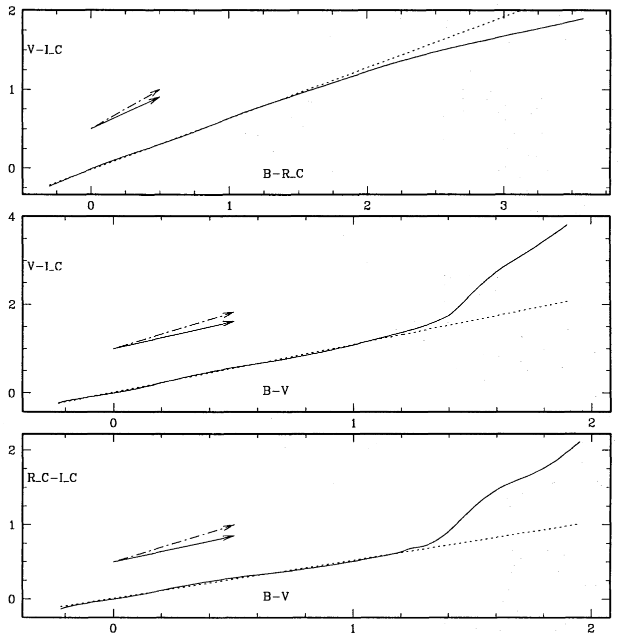

Fig. 2. The ZAMS and linear fit for some color combinations. The solid and dashed arrows show the reddening vector for the R_V=3.1 and R_V=5.0 laws, respectively.

$$\text{[for } +0.40 \leq (\mathrm{B-V})_\circ \leq +0.80]$$
$$(B-I_C)_\circ = -0.262 + 2.350 \times (B-V)_\circ \quad (19)$$
$$\text{[for } +0.80 \leq (\mathrm{B-V})_\circ \leq +1.30]$$

Comparing Eqs. (5),(6),(17) and (19) it is evident that between $+0.05 \leq (B-V)_\circ \leq +0.40$ and $+0.80 \leq (B-V)_\circ \leq +1.30$ the ZAMS is exactly or closely parallel to the reddening vector (i.e. $\gamma \equiv \beta$). *In these color ranges no reliable reddening determination is possible when the M 90 extinction law for R_V=3.1 applies*. To state it more clearly, suppose to apply the method to a cluster for which photometry is available only for stars in these two color ranges. If a reddening determination is attempted using the broad range linear fit given in Eq. (10), a non-sense $E_{(B-V)}$ value will be obtained.

The conclusion is that careful judgment is necessary prior to the application of the method, with a careful evaluation point-by-point along the ZAMS.

5. Other color-color combinations

We have explored the applicability of the method to other combinations of colors excluding those involving the U band, because their behaviour can be anticipated to be very non-linear. The useful color combinations have to satisfy two basic requirements: (a) the bluest portion of the ZAMS must satisfactorly be fitted with a first order polinomyal (cf. Eq. 1), and (b) the value $\gamma - \beta$ should be as large as possible (cf. Eq.5). All the color combinations perform poorly or are totally useless. Among those that could be used in some way, there are $(B-V)$ vs. (R_C-I_C), $(B-V)$ vs. $(V-I_C)$ and $(B-R_C)$ vs. $(V-I_C)$. The ZAMS, linear fits and reddening vectors are shown in Fig. 2. For these combinations, Eq. (1) and (5) become:

$$(B-V)_\circ = +0.012 + 0.512 \times (R_C - I_C)_\circ \quad (20)$$
$$E_{(B-V)} = \frac{Q-0.012}{0.198} \quad \text{[for the } R_V = 3.1 \text{ law]} \quad (21)$$
$$E_{(B-V)} = \frac{Q-0.012}{0.488} \quad \text{[for the } R_V = 5.0 \text{ law]} \quad (22)$$

valid for $-0.23 \leq (B-V)_\circ \leq +1.20$,

$$(B-V)_\circ = +0.020 + 1.080 \times (V - I_C)_\circ \quad (23)$$
$$E_{(B-V)} = \frac{Q-0.020}{0.170} \quad \text{[for the } R_V = 3.1 \text{ law]} \quad (24)$$
$$E_{(B-V)} = \frac{Q-0.020}{0.580} \quad \text{[for the } R_V = 5.0 \text{ law]} \quad (25)$$

valid for $-0.23 \leq (B-V)_\circ \leq +1.20$,

$$(B-R_C)_\circ = -0.017 + 0.647 \times (V - I_C)_\circ \quad (26)$$
$$E_{(B-R_C)} = \frac{Q+0.017}{0.163} \quad \text{[for the } R_V = 3.1 \text{ law]} \quad (27)$$
$$E_{(B-R_C)} = \frac{Q+0.017}{0.353} \quad \text{[for the } R_V = 5.0 \text{ law]} \quad (28)$$

valid for $-0.30 \leq (B-R_C)_\circ \leq +1.40$.

However, for all these color combinations the same warning accurred before about the $(B-V)$, $(B-I_C)$ relation holds true: the linear fits depart from the local slope of the ZAMS in one or more points along the range of applicability to such an extent to vanish the quantity $(\gamma - \beta)$. Therefore, they must be used carefully.

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