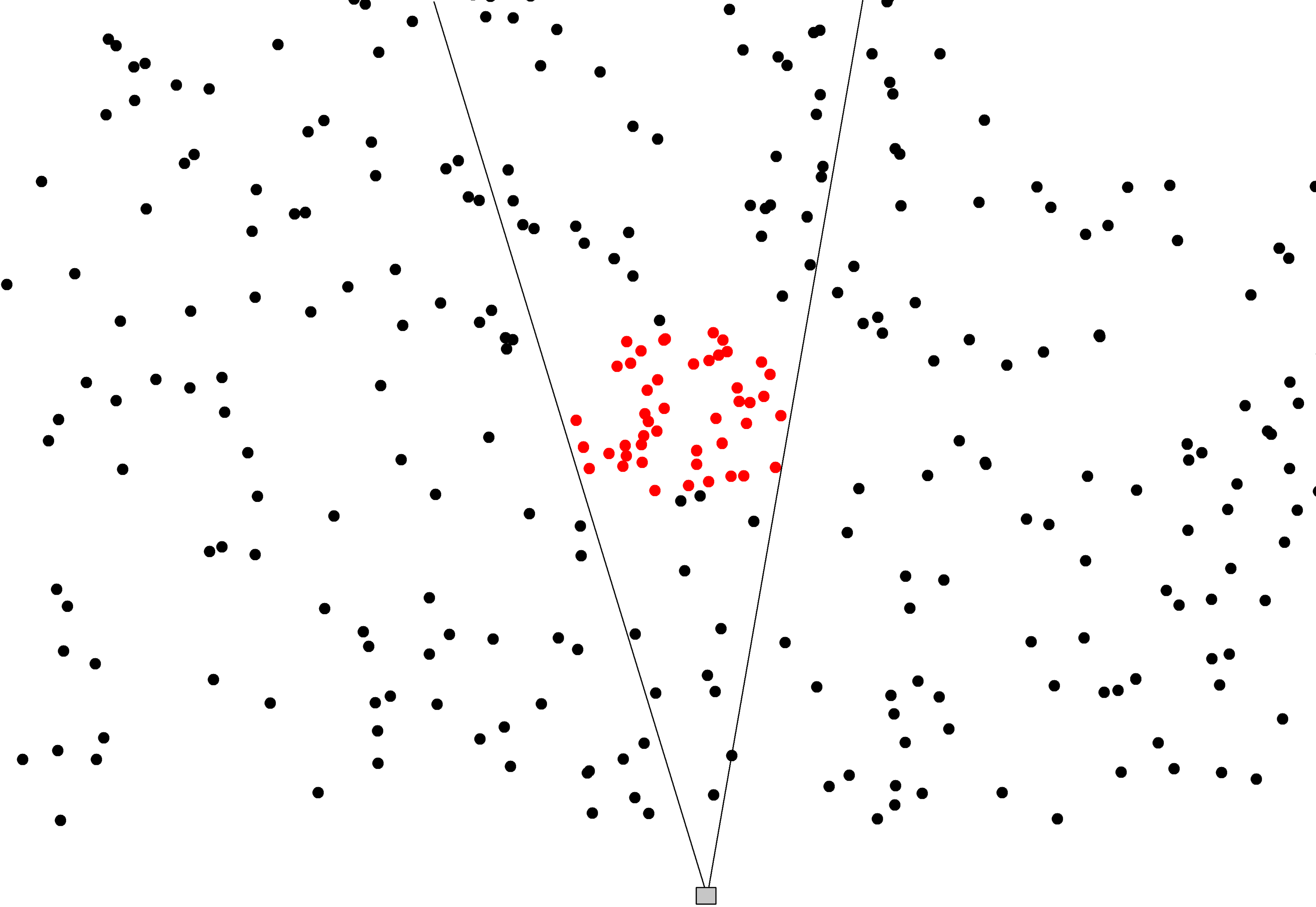
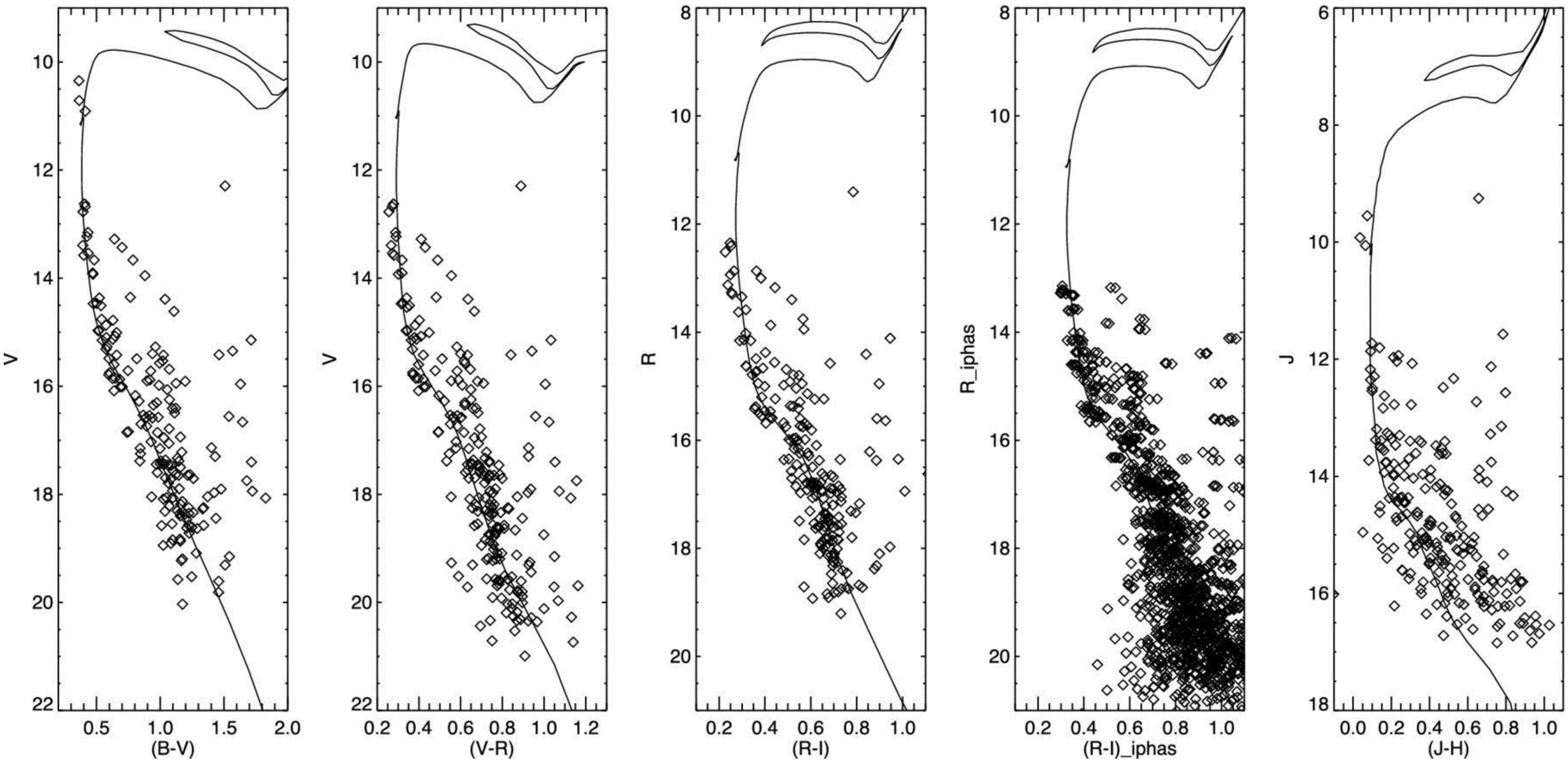
The free cluster parameters

1. Reddening
2. Distance modulus
3. Age
4. Metallicity

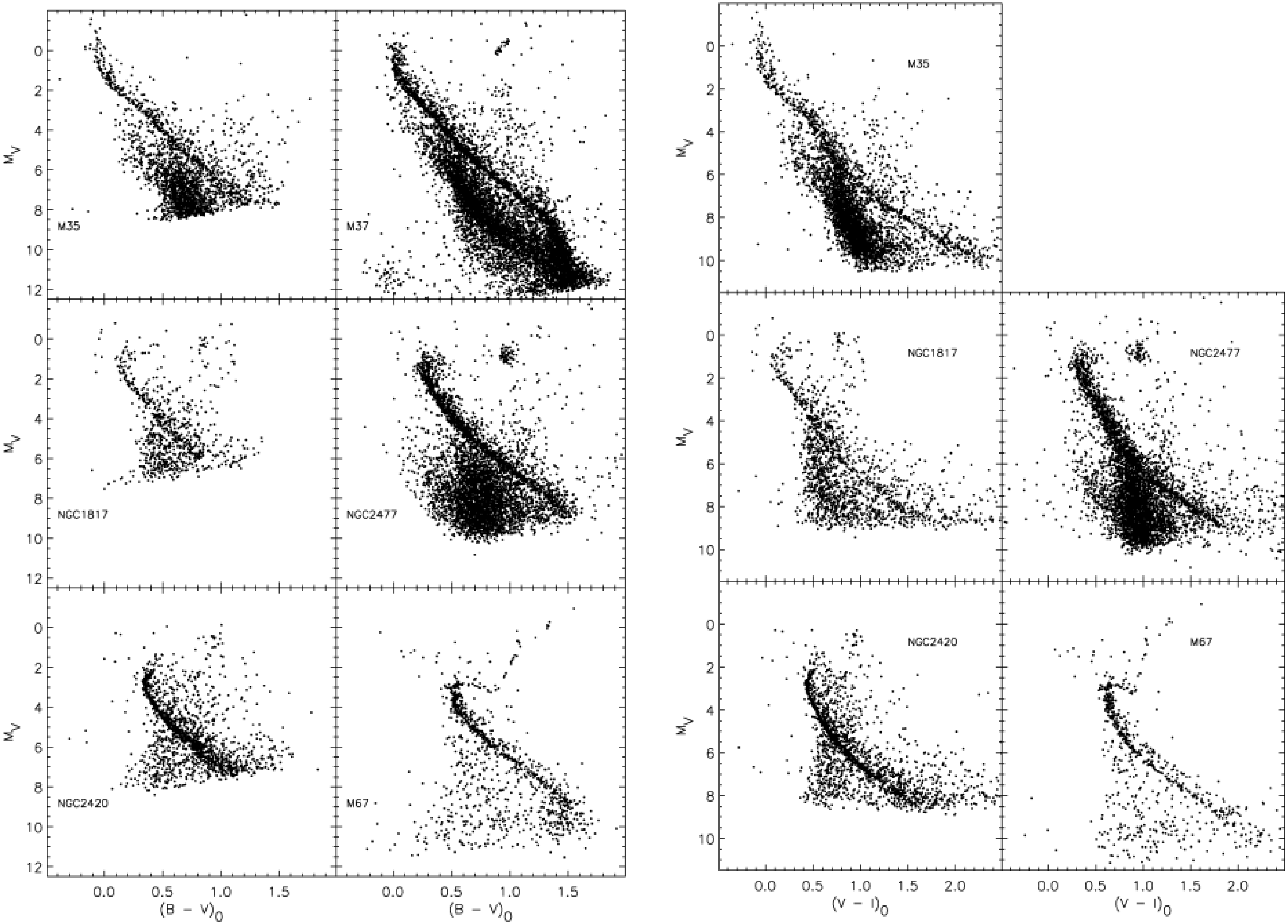
Determination in the order: Reddening, age, distance modulus simultaneously, metallicity with possible iterations



Color – Magnitude - Diagram



Glushkova et al., 2013, MNRAS, 429, 1102



Grocholski & Sarajedini, 2003, MNRAS, 345, 1015

Different photometric indices

Several different indices et al. are available (very much incomplete):

- Sensitive to temperature:
  1. Johnson: B-V, V-I, R-I, V-K, …
  2. Strömgren: b-y, u-b, β
  3. Geneva: B2-V1, X, …
  4. 2MASS: H-K, J-K and H-J
- „Mixture“:
  1. Johnson: U-B
  2. Strömgren: c_1, m_1, …
  3. Geneva: d, D, m_2, …

How to derive cluster parameters?

- Program „HR – Trace“, very good for training: http://xoomer.virgilio.it/hrtrace/index.htm
- Use as much as possible available indices
- Check the literature for published values as least as a starting point
- First try it with a “standard set” of data

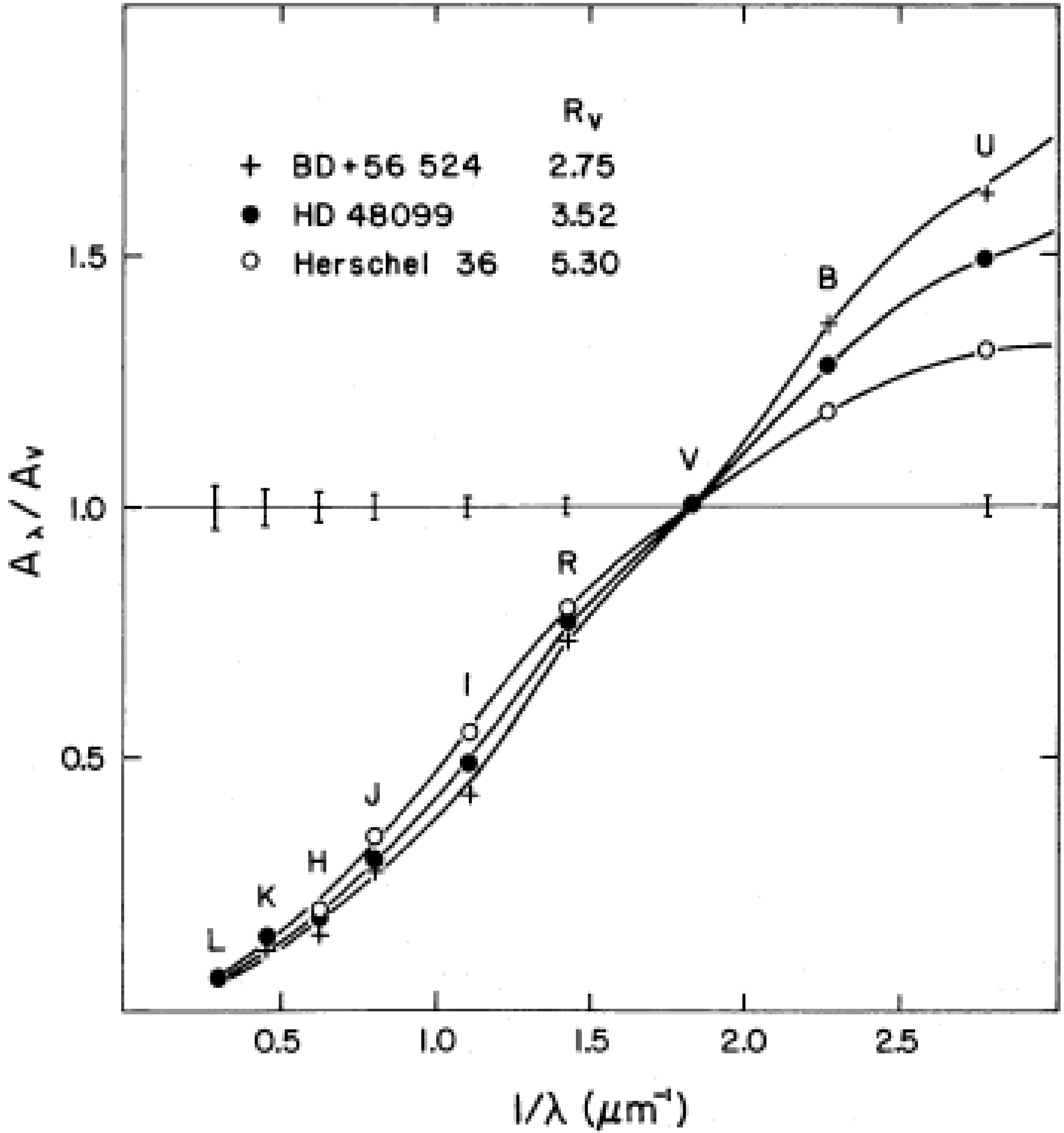
Absorption = Extinction = Reddening

- $A_V = k_1 E(B\text{-}V) = k_2 E(V\text{-}R) = \ldots$
- General extinction because of the ISM characteristics between the observer and the object
- Differential extinction within one star cluster because of local environment
- Both types are, in general wavelength dependent

Reasons for the interstellar extinction

- Light scatter at the interstellar dust
- Light absorption => Heating of the ISM
- Depending on the composition and density of the ISM
- Main contribution due to dust
- Simulations and calculations in Cardelli et al., 1989, ApJ, 345, 245

Cardelli et al., 1989, ApJ, 345, 245



Important parameter:

$R_V = A_V/E(B-V)$

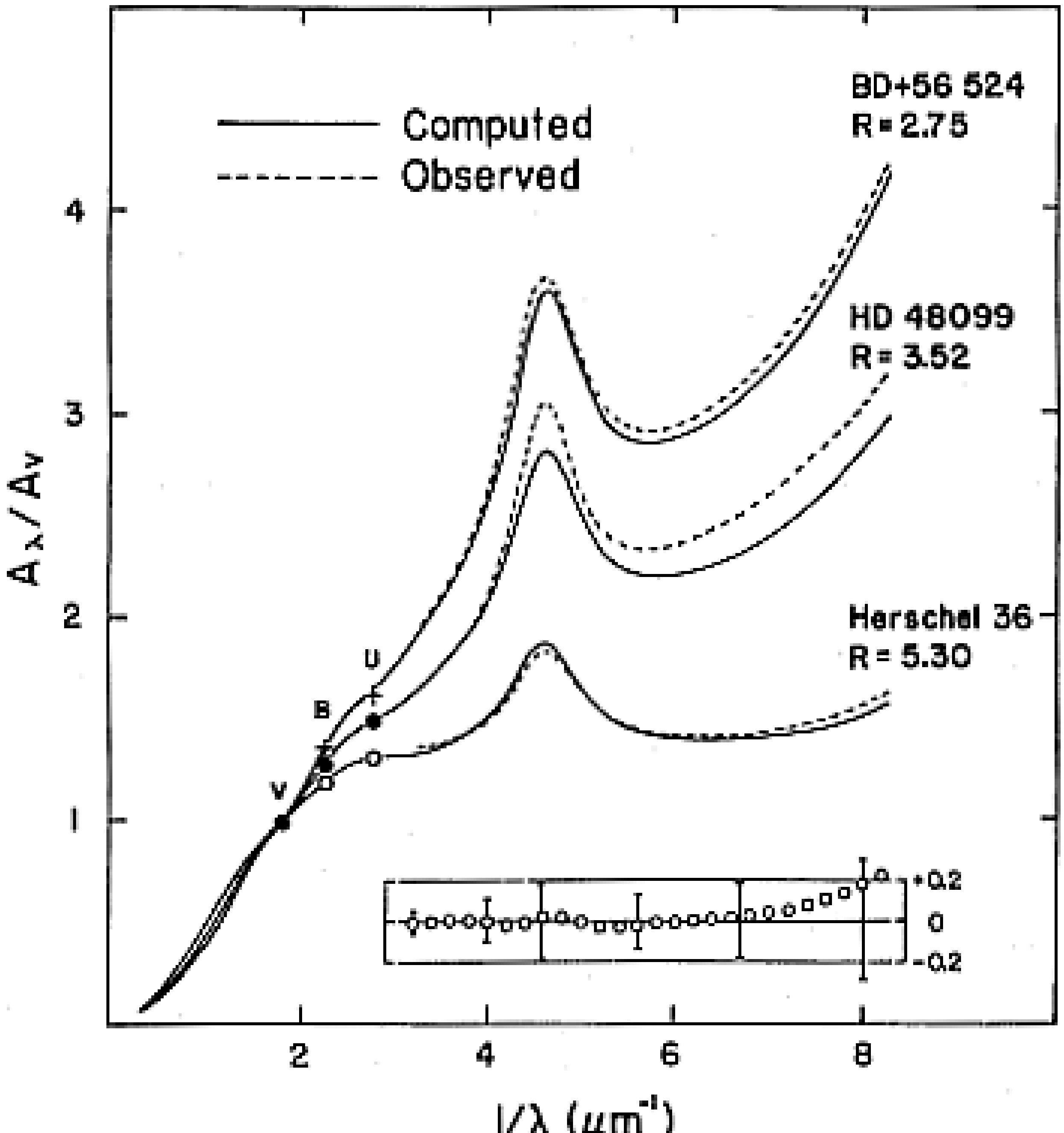
Normalization factor

Standard value used is 3.1

Be careful, different values used!

Depending on the line of sight

Cardelli et al., 1989, ApJ, 345, 245



Dependency of the extinction from R_V

How to derive the reddening?

- Non-Isochrone approach: from photometric and spectroscopic observations

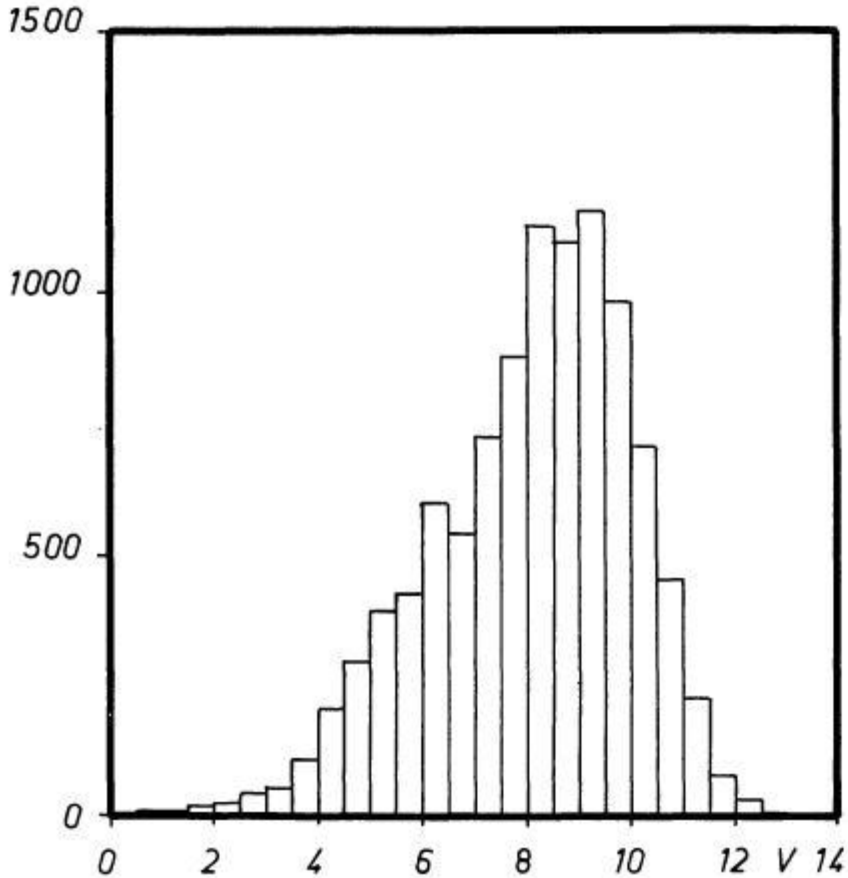


FIGURE 2. — Distribution of the stars *versus* apparent *V*-magnitude.

Classical approach: Neckel & Klare, 1980, A&AS, 42, 251

Take all available UBV and Strömgren β photometry

MK classifications

4. **Extinction values and distances.** — The visual extinction A_v can be derived from

$$A_v = R\{(B-V)-(B-V)_0\}. \quad (2)$$

For R we take the value 3.1.

The intrinsic color $(B\text{-}V)_0$ follows directly from the MK calibration, if the MK type is known. In addition, $(B\text{-}V)_0$ can also be derived from the UBV and β data. The distance moduli are then given by

$$V - M_v - A_v = 5 \lg r - 5. \quad (3)$$

If we could derive A_v and r by both methods, we could use the mean values of extinction and distance moduli. This was possible for 1 020 stars. Figure 4 shows the frequency distribution of the differences

$$D = (V - M_v(\mathrm{MK}) - A_v(UBV, \mathrm{MK})) - \\ - (V - M_v(\beta) - A_v(UBV, \beta)). \quad (4)$$

Bailer-Jones, 1996, PhD, Cambridge University

SpT	Spectral Type	II	II/III	III	III/IV	IV	IV/V	V
		Absolute Magnitude						
1	O3	-	-	-	-	-	-	-
2	O4	-	-	-	-	-	-	-
3	O5	-8.20	-7.70	-7.20	-6.80	-6.40	-5.90	-5.60
4	O6	-7.60	-7.20	-6.85	-6.50	-6.10	-5.70	-5.40
5	O7	-7.00	-6.80	-6.60	-6.30	-5.90	-5.50	-5.20
6	O8	-6.50	-6.30	-6.20	-5.90	-5.60	-5.30	-5.00
7	O9	-6.00	-5.85	-5.70	-5.50	-5.30	-5.00	-4.70
8	B0	-5.40	-5.20	-5.00	-4.90	-4.80	-4.50	-4.20
9	B1	-5.00	-4.70	-4.40	-4.20	-4.00	-3.80	-3.60
10	B2	-4.80	-4.20	-3.60	-3.35	-3.10	-2.80	-2.50
11	B3	-4.60	-3.85	-3.10	-2.80	-2.50	-2.10	-1.70
12	B4	-4.50	-3.57	-2.55	-2.40	-2.15	-1.75	-1.35
13	B5	-4.40	-3.30	-2.20	-2.00	-1.80	-1.40	-1.00
14	B6	-4.20	-3.05	-1.90	-1.70	-1.50	-1.20	-0.70
15	B7	-4.00	-2.80	-1.60	-1.40	-1.20	-0.80	-0.40
16	B8	-3.80	-2.60	-1.00	-0.85	-0.70	-0.35	0.00
17	B9	-3.60	-2.45	-0.40	-0.30	-0.20	0.15	0.50
18	A0	-3.20	-1.90	0.10	0.20	0.30	0.65	1.00
19	A1	-3.00	-1.75	0.50	0.60	0.70	1.00	1.30
20	A2	-2.90	-1.65	0.70	0.85	1.00	1.30	1.60
21	A3	-2.80	-1.60	0.90	1.05	1.20	1.40	1.80
22	A4	-2.80	-1.55	1.05	1.15	1.30	1.63	1.95
23	A5	-2.70	-1.50	1.10	1.25	1.40	1.75	2.10

Assume V = 10 mag and no reddening

O5: -5.6 => 13 000 pc
A0: +1.0 => 630 pc
G0: +4.5 => 125 pc
M0: +8.9 => 15 pc

Assume V = 20 mag and no reddening

O5: -5.6 => 1.3 Mpc
A0: +1.0 => 63 kpc
G0: +4.5 => 12.5 kpc
M0: +8.9 => 1.5 kpc

24	A6	−2.65	−1.45	1.15	1.35	1.60	1.95	2.30
25	A7	−2.60	−1.40	1.20	1.50	1.80	2.10	2.40
26	A8	−2.60	−1.40	1.30	1.65	2.05	2.25	2.50
27	A9	−2.55	−1.35	1.40	1.75	2.10	2.35	2.60
28	F0	−2.50	−1.30	1.50	1.85	2.20	2.45	2.70
29	F2	−2.50	−1.30	1.60	2.00	2.40	2.75	3.10
30	F3	−2.40	−1.20	1.65	2.10	2.45	2.90	3.35
31	F5	−2.30	−1.10	1.70	2.10	2.50	3.05	3.60
32	F6	−2.25	−1.05	1.75	2.15	2.55	3.18	3.80
33	F7	−2.20	−1.00	1.75	2.15	2.60	3.30	4.00
34	F8	−2.20	−1.00	1.75	2.20	2.80	3.50	4.20
35	G0	−2.10	−0.95	1.70	2.15	2.90	3.70	4.45
36	G1	−2.05	−0.90	1.70	2.10	3.00	3.80	4.70
37	G2	−2.00	−0.90	1.60	2.10	3.00	3.90	4.80
38	G3	−2.00	−0.85	1.60	2.05	3.05	4.00	5.00
39	G5	−2.00	−0.85	1.60	2.00	3.10	4.15	5.20
40	G6	−2.00	−0.80	1.50	2.00	3.15	4.23	5.30
41	G8	−2.00	−0.80	1.35	1.95	3.20	4.35	5.50
42	K0	−2.00	−0.80	1.20	1.87	3.20	4.50	5.80
43	K1	−2.00	−0.85	1.00	1.80	3.30	4.70	6.10
44	K2	−2.00	−0.90	0.80	1.80	3.30	4.80	6.30
45	K3	−2.00	−1.00	0.60	1.80	3.40	5.00	6.60
46	K4	−2.10	−1.00	0.20	–	–	–	6.90
47	K5	−2.20	−1.00	0.00	–	–	–	7.50
48	M0	−2.40	−1.00	−1.10	–	–	–	8.90
49	M1	−2.50	−1.10	−0.40	–	–	–	9.60
50	M2	−2.50	−1.10	−0.60	–	–	–	10.30
51	M3	−2.50	−1.20	−0.70	–	–	–	10.80
52	M4	−2.50	−1.20	−0.80	–	–	–	11.40
53	M5	−2.50	−1.30	−0.90	–	–	–	12.30
54	M6	−2.50	−1.30	−1.00	–	–	–	13.20
55	M7	−2.50	−1.40	−1.10	–	–	–	14.00
56	M8	−2.50	−1.50	−1.20	–	–	–	16.50
57	M9	–	–	–	–	–	–	–

TABLE V. The $M_v(\beta)$ calibration.

β (mag)	$M_v(\beta)$ (mag)	β (mag)	$M_v(\beta)$ (mag)
2.560	−6.51	2.720	−0.27
2.570	−5.84	2.730	−0.10
2.580	−5.22	2.740	0.04
2.590	−4.65	2.750	0.18
2.600	−4.12	2.760	0.30
2.610	−3.62	2.770	0.41
2.620	−3.17	2.780	0.51
2.630	−2.75	2.790	0.60
2.640	−2.36	2.800	0.68
2.650	−2.01	2.810	0.76
2.660	−1.69	2.820	0.83
2.670	−1.39	2.830	0.90
2.680	−1.12	2.840	0.97
2.690	−0.87	2.850	1.03
2.700	−0.65	2.860	1.10
2.710	−0.45	2.870	1.17
		2.880	1.24
		2.890	1.31
		2.900	1.39

Crawford, 1976, AJ, 83, 48

Example for the β index

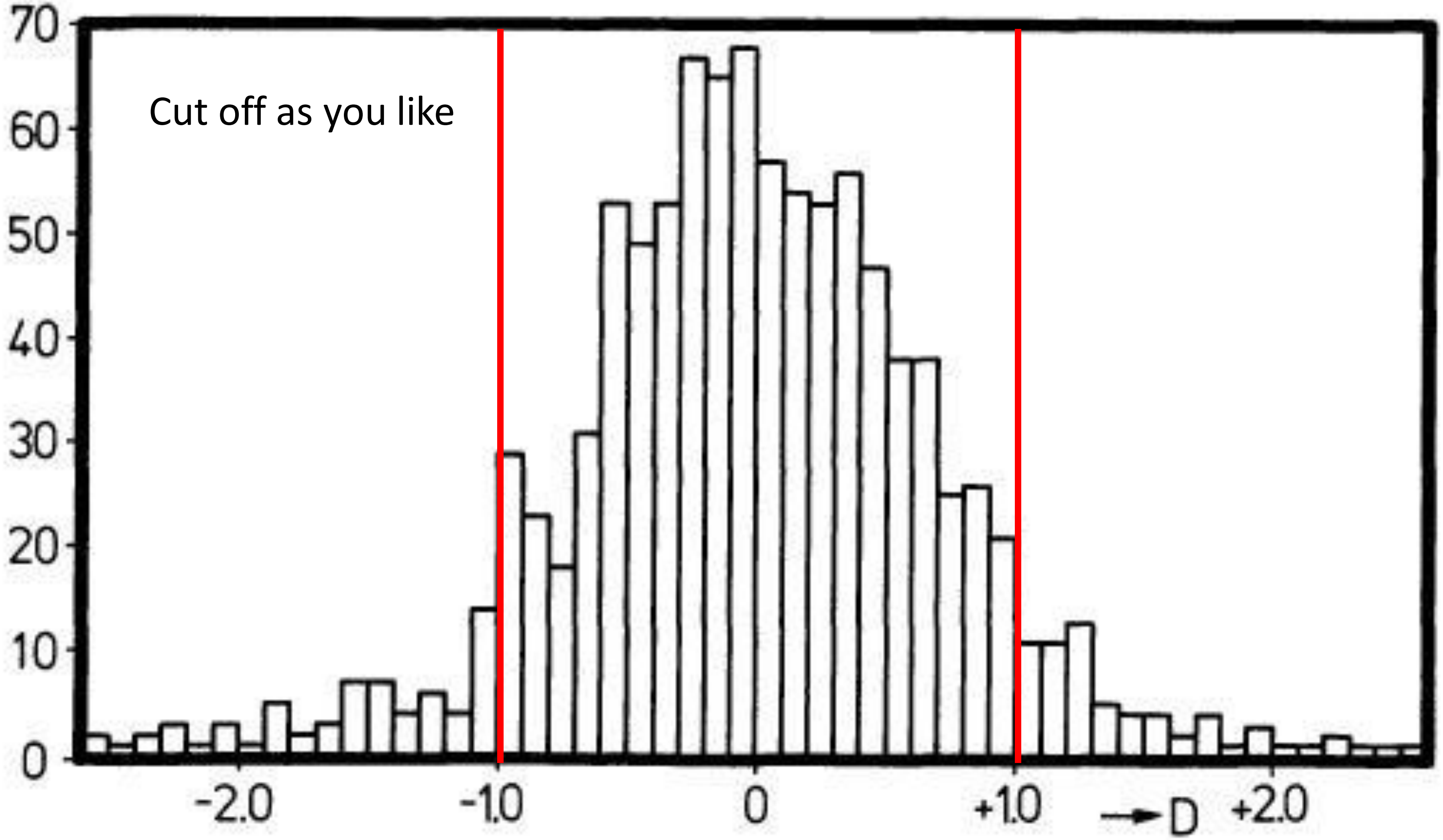
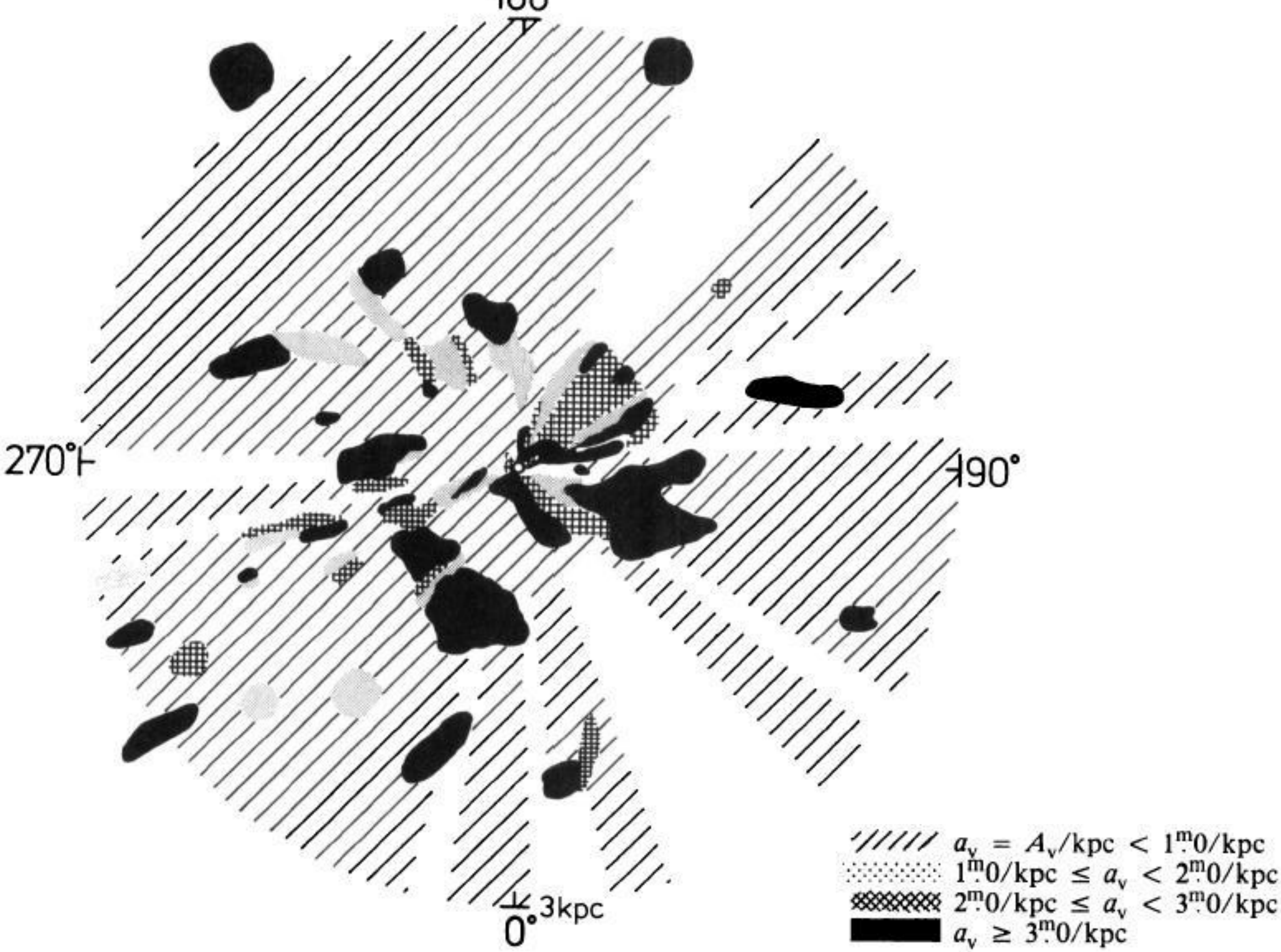
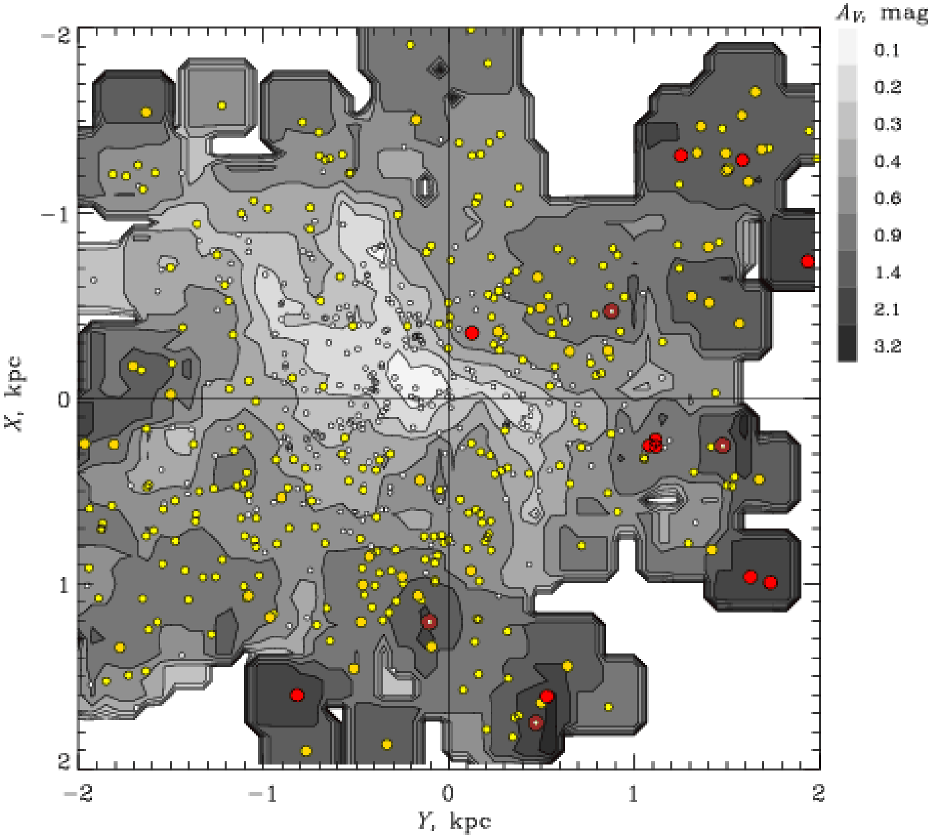
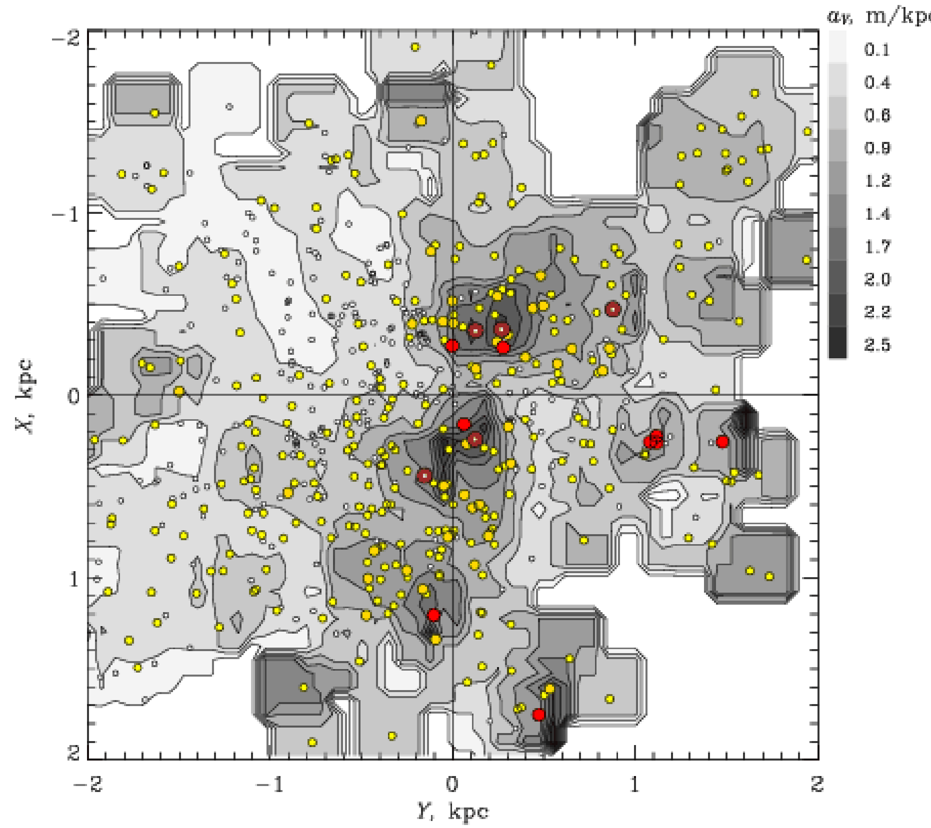


FIGURE 4. — Frequency distribution of the differences between the distance moduli derived from *UBV* + MK and *UBV* + β data.

Neckel & Klare, 1980, A&AS, 42, 251





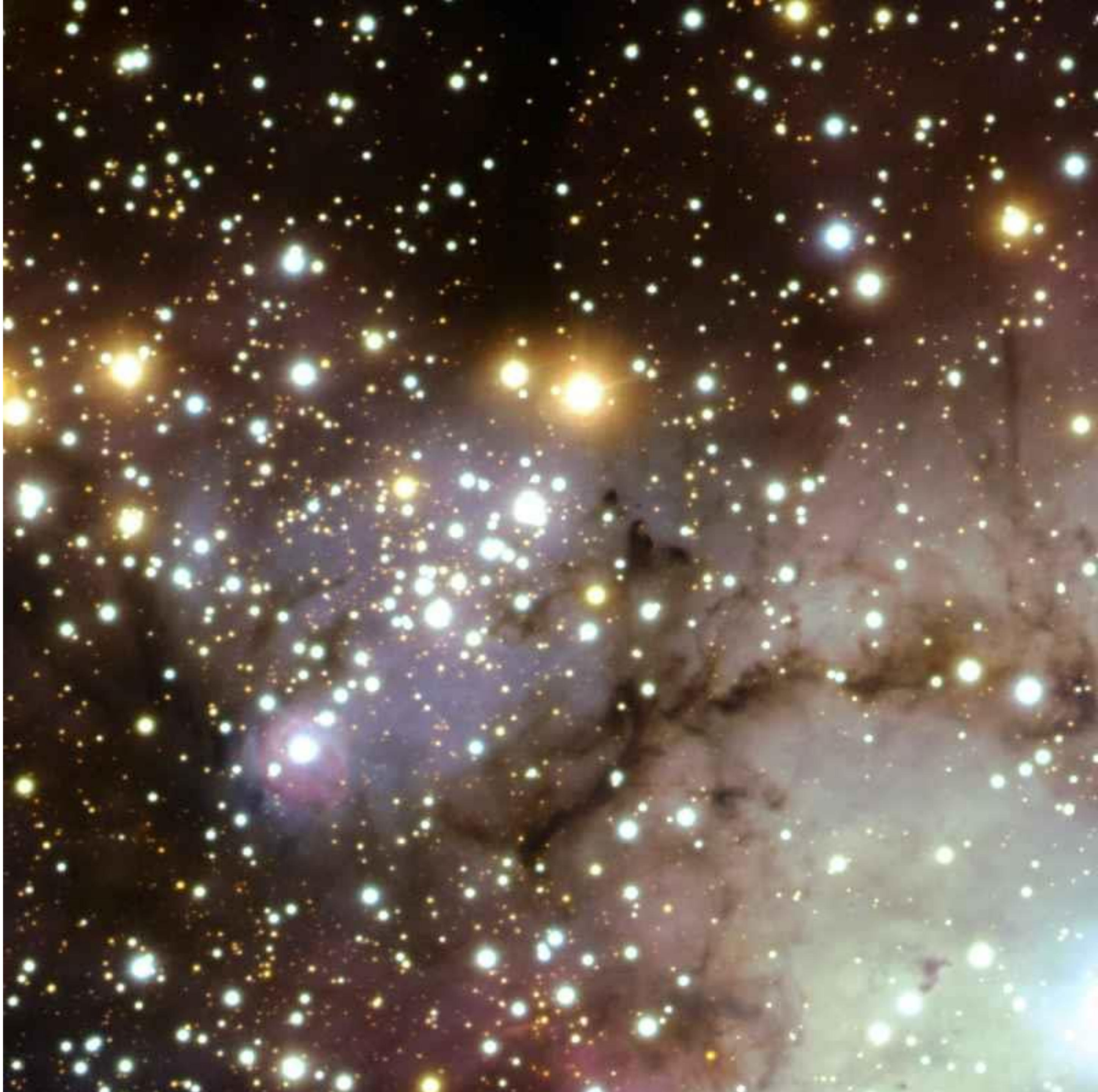


Piskunov et al., 2006, A&A, 445, 545

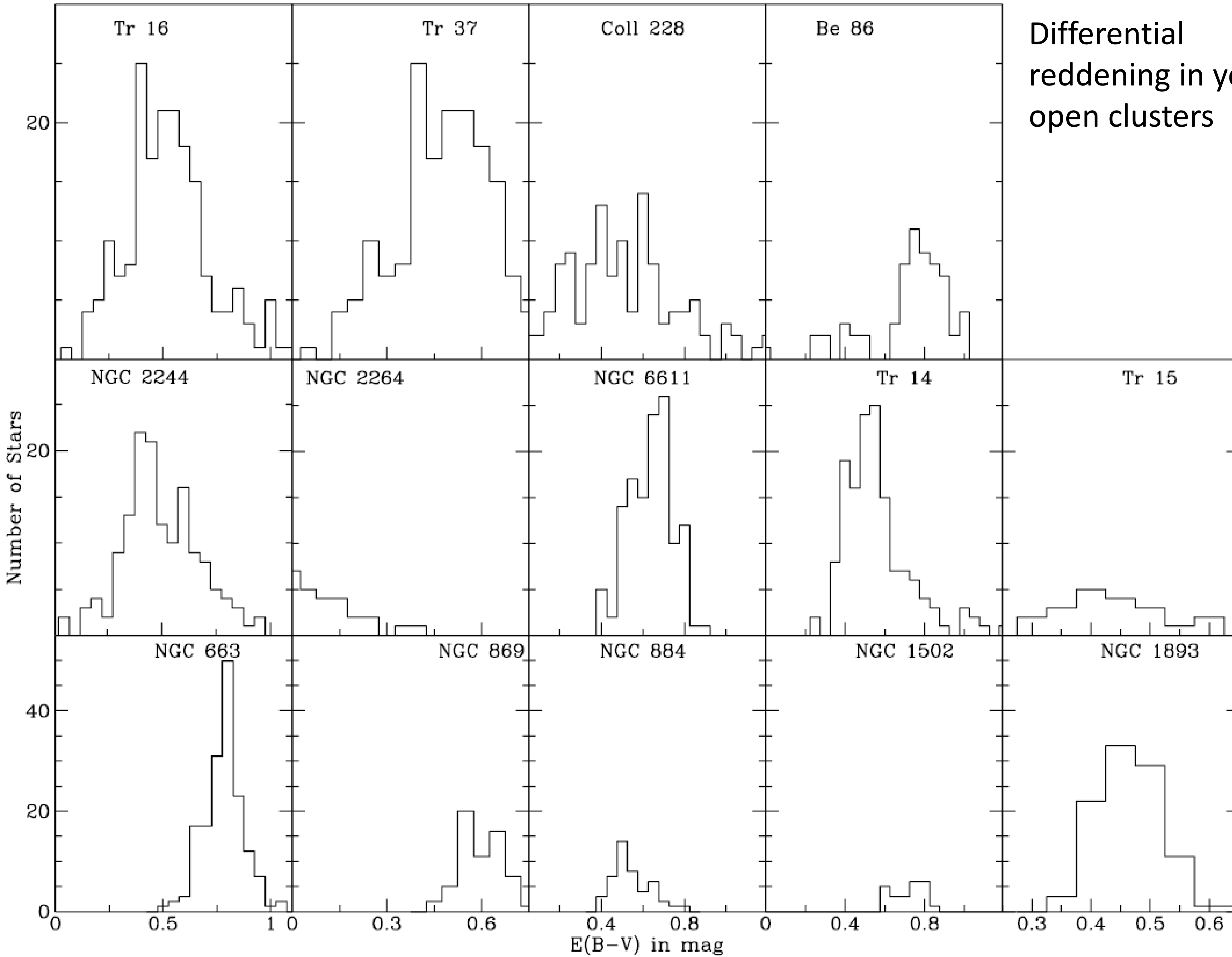
Haffner 18

Age about 8 Myr
d = 6000 pc

differential extinction within the cluster



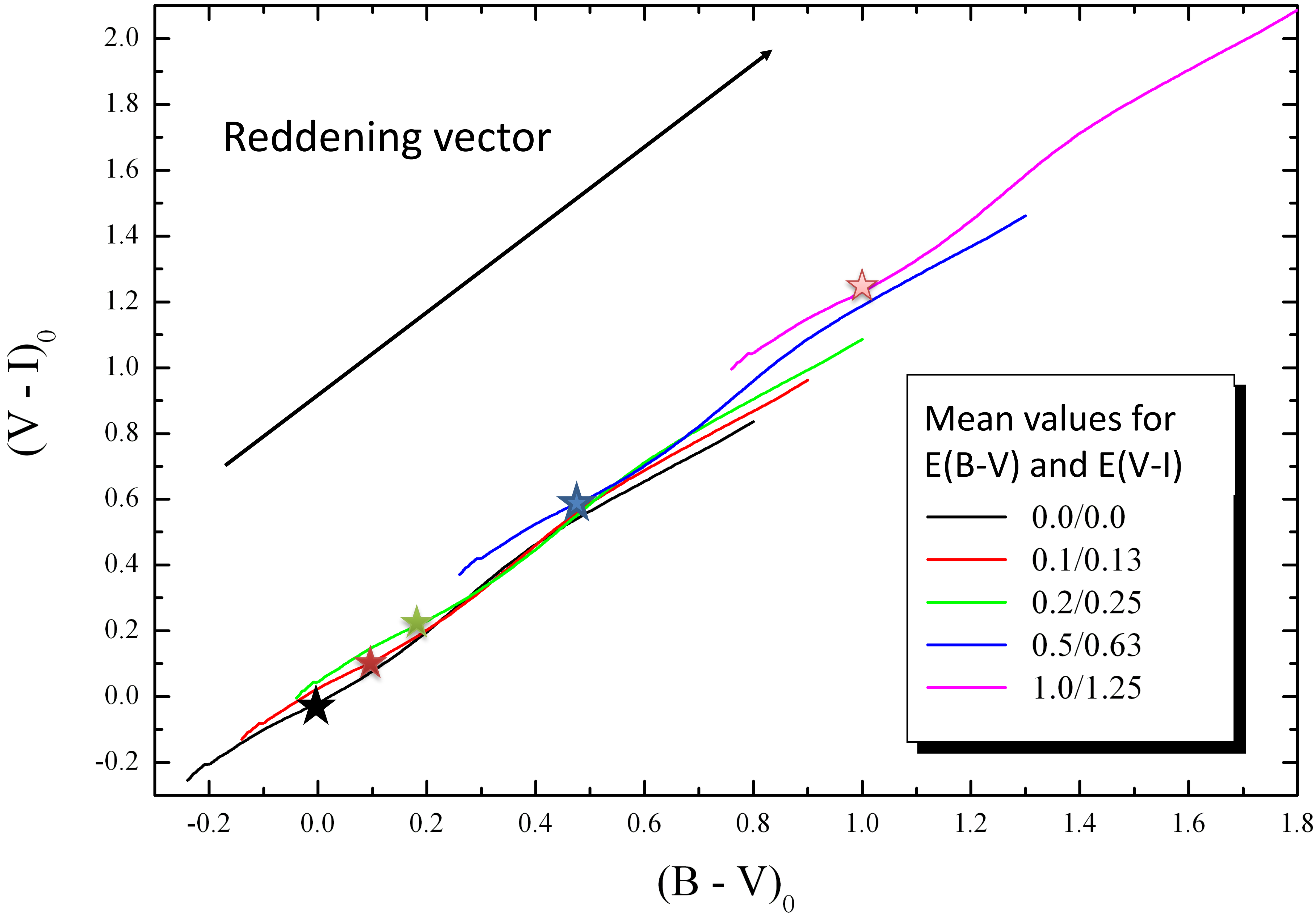
Differential reddening in young open clusters



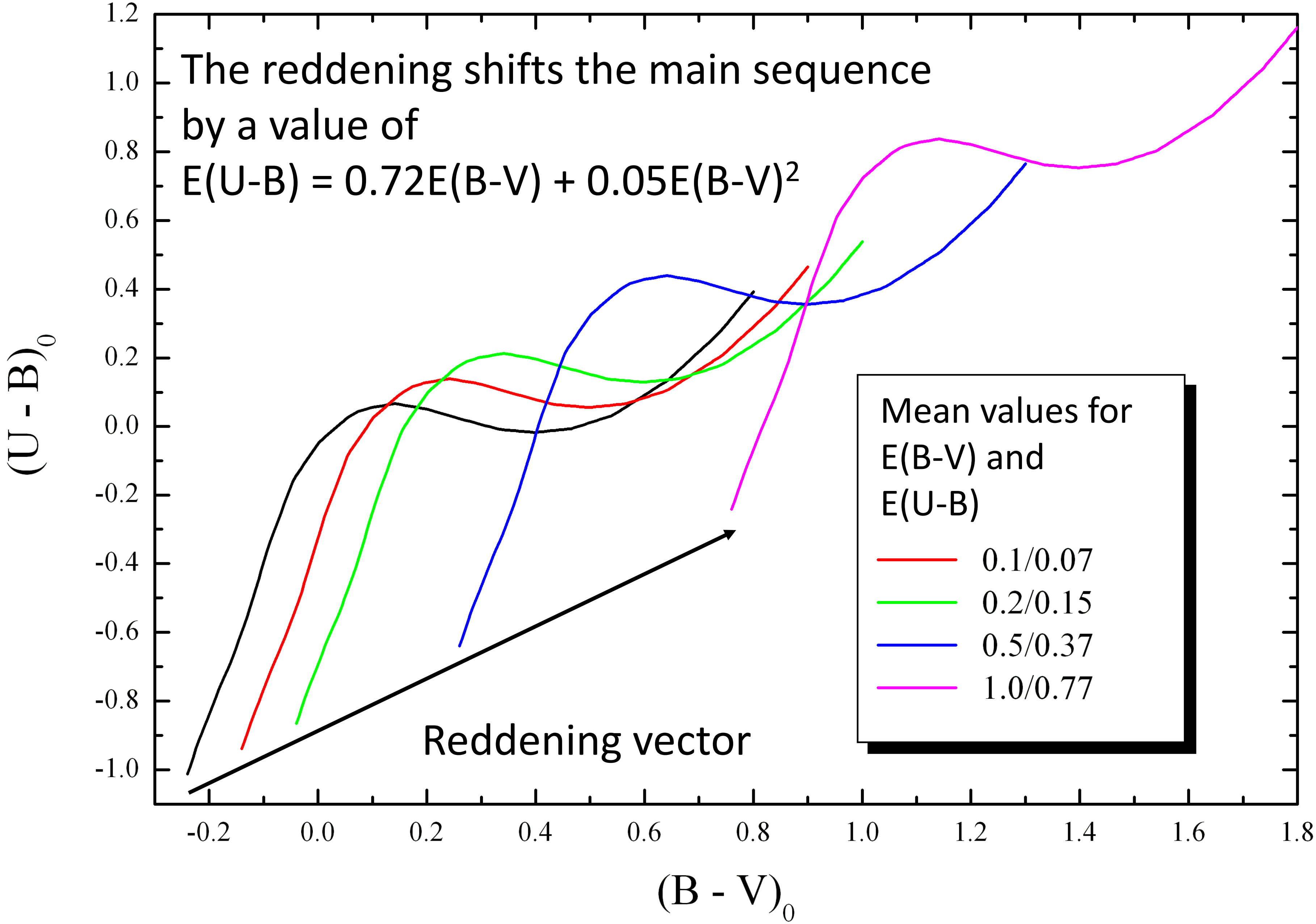
Yadav & Sagar, 2001, MNRAS, 328, 370

Determination of the reddening - Isochrones

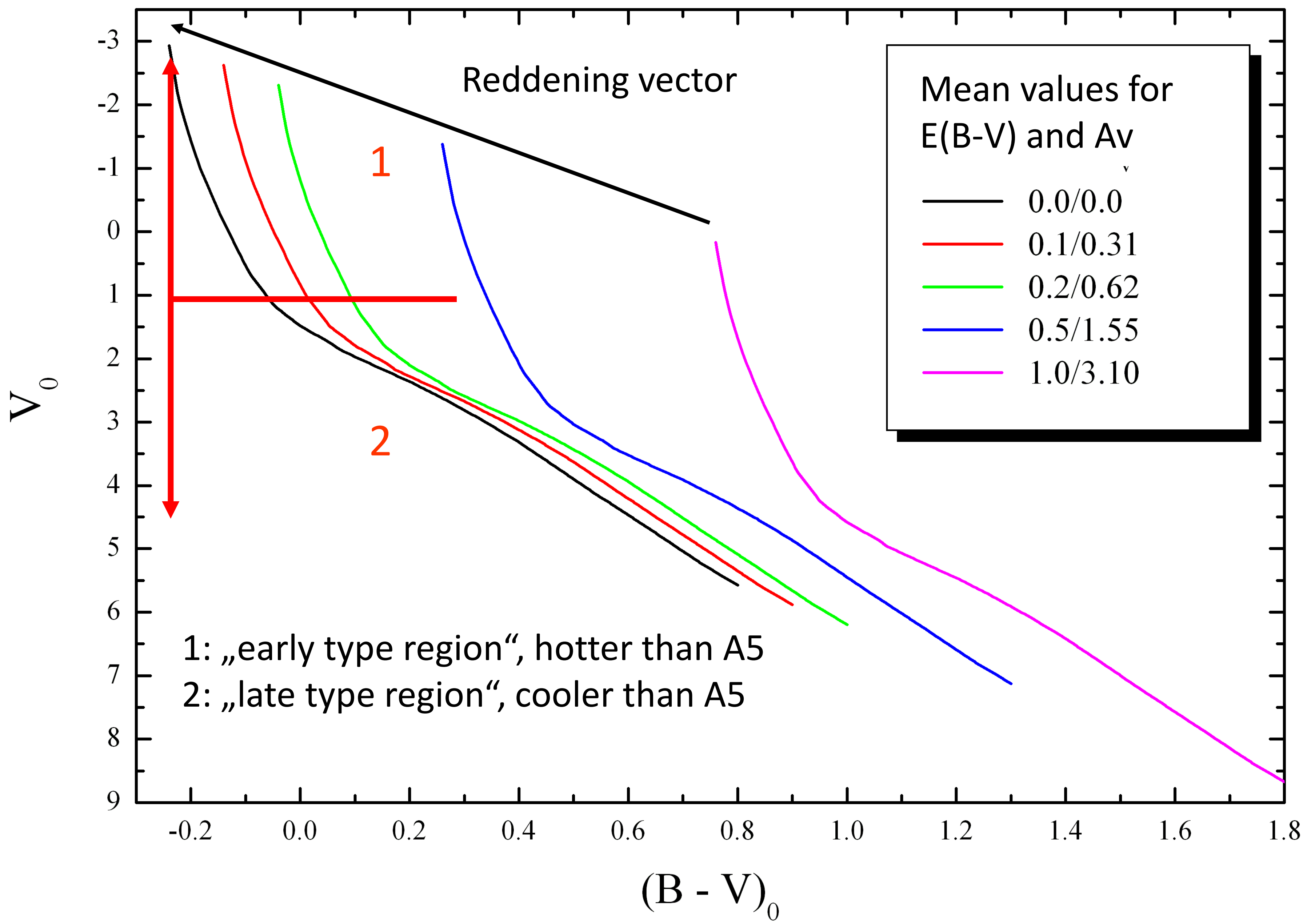
- From two temperature sensitive parameters, the determination of the reddening is not possible
- You need one “other” observational index
- First choices: (U – B), (u – b), [X], β
- Normally, you only have V, J, H, K, and so on



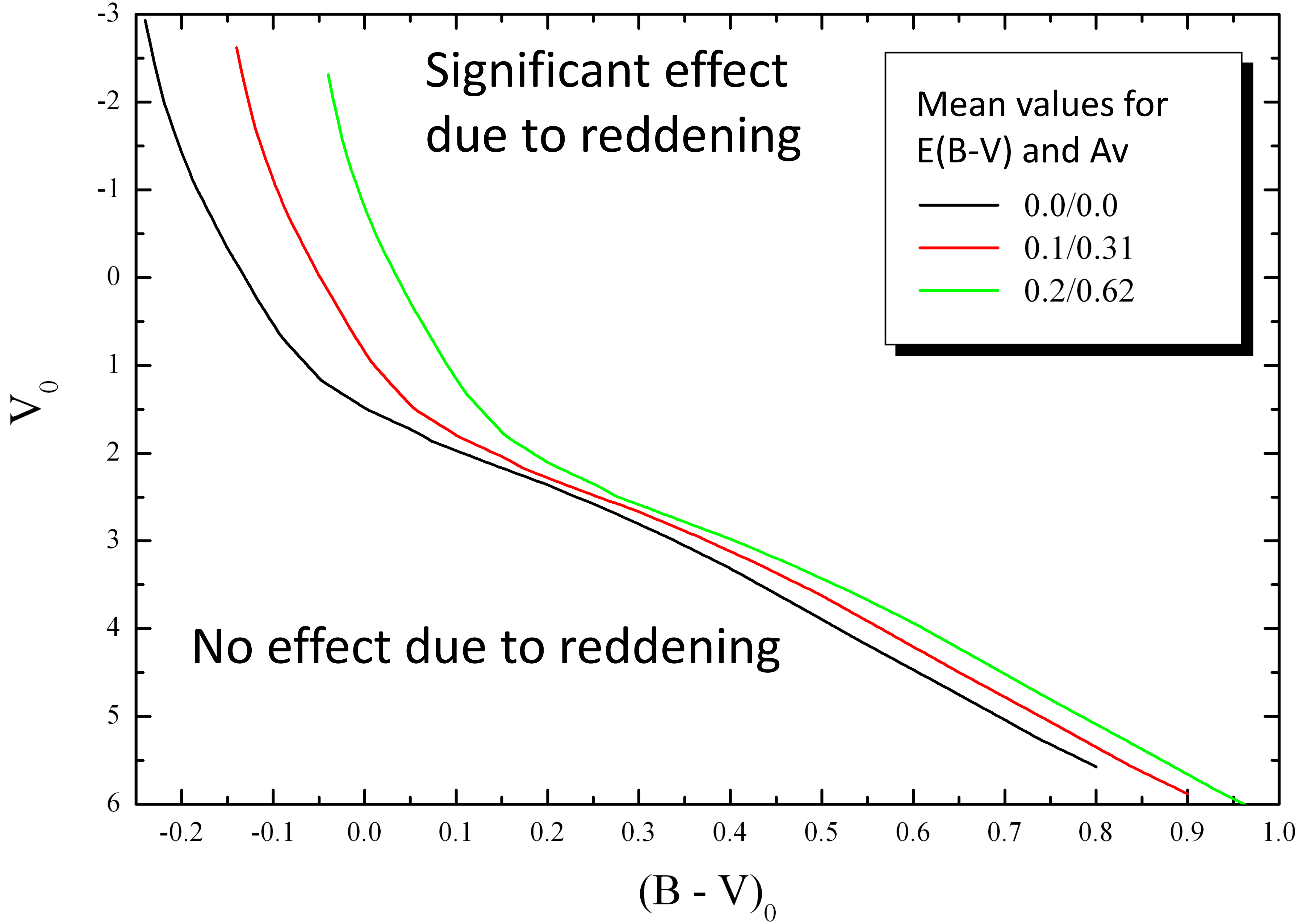
You would need a spectral information



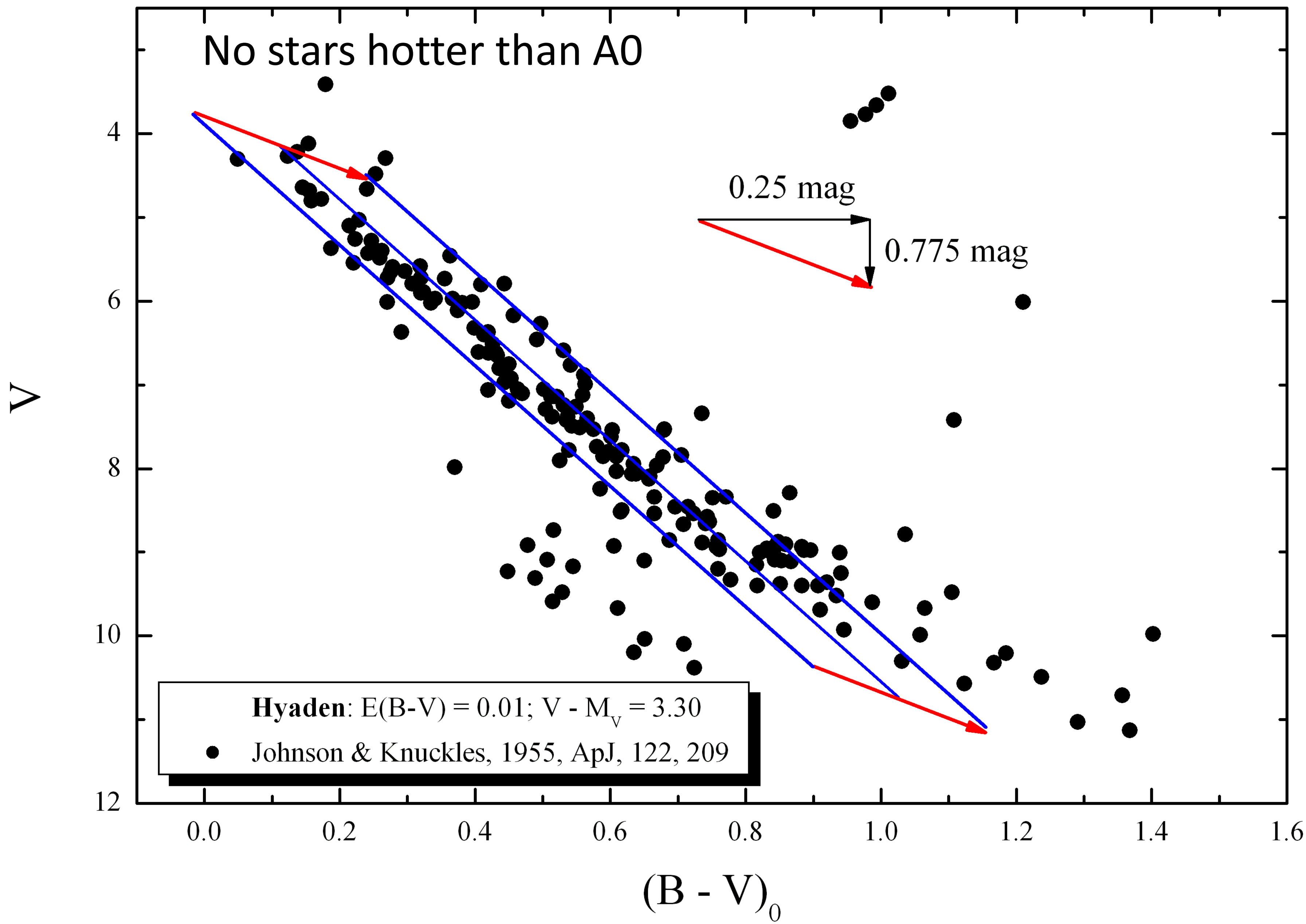
The reddening shifts the main sequence
by a value of
E(U-B) = 0.72E(B-V) + 0.05E(B-V)2
Mean values for
E(B-V) and
E(U-B)
0.1/0.07
0.2/0.15
0.5/0.37
1.0/0.77
Reddening vector
(U - B)0
(B - V)0
1.2
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
-0.2
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8



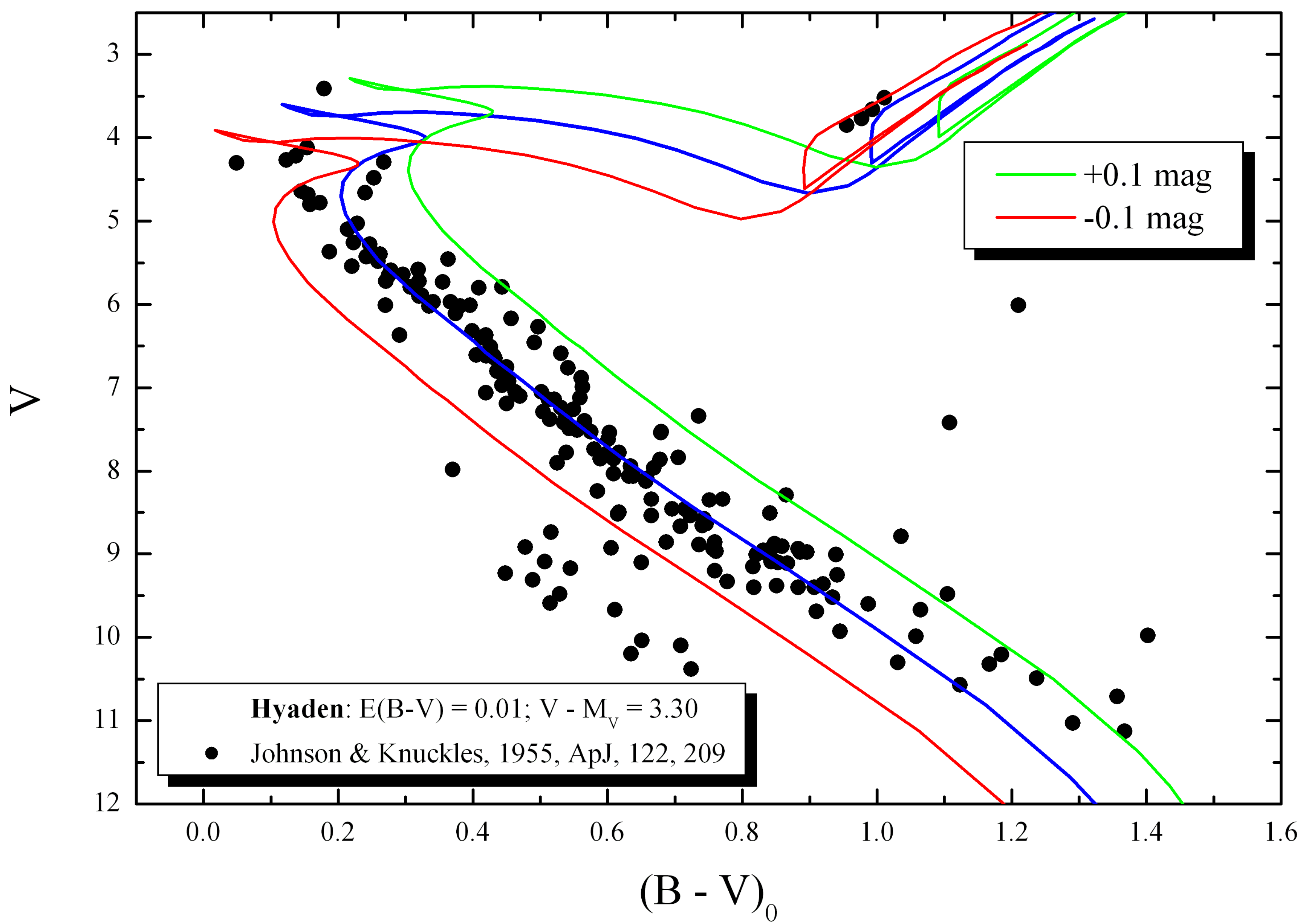
Reddening vector
Mean values for
E(B-V) and Av
0.0/0.0
0.1/0.31
0.2/0.62
0.5/1.55
1.0/3.10
1
2
1: „early type region“, hotter than A5
2: „late type region“, cooler than A5
V_0
$(B - V)_0$
-3
-2
-1
0
1
2
3
4
5
6
7
8
9
-0.2
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8



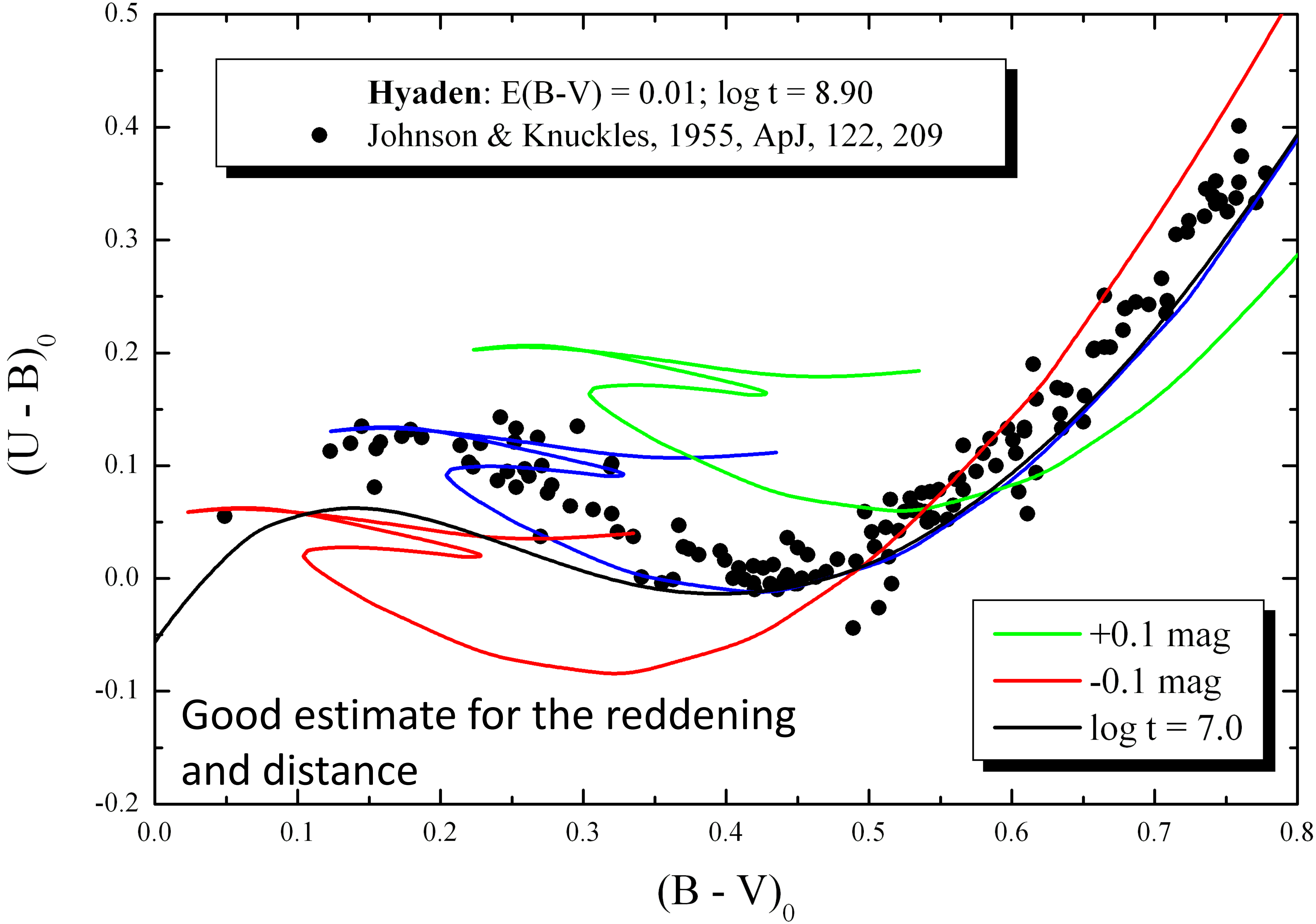
Significant effect due to reddening
No effect due to reddening
Mean values for E(B-V) and Av
0.0/0.0
0.1/0.31
0.2/0.62
V0
(B - V)0
-3
-2
-1
0
1
2
3
4
5
6
-0.2
-0.1
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0



No stars hotter than A0
0.25 mag
0.775 mag
V
$(B - V)_0$
4
6
8
10
12
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
Hyaden: E(B-V) = 0.01; V - M_V = 3.30
Johnson & Knuckles, 1955, ApJ, 122, 209



+0.1 mag
-0.1 mag
Hyaden: E(B-V) = 0.01; V - M$_V$ = 3.30
Johnson & Knuckles, 1955, ApJ, 122, 209
V
(B - V)$_0$


Hyaden: E(B-V) = 0.01; log t = 8.90
Johnson & Knuckles, 1955, ApJ, 122, 209
+0.1 mag
-0.1 mag
log t = 7.0
Good estimate for the reddening and distance
(U - B)$_0$
(B - V)$_0$
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8

4. **Extinction values and distances.** — The visual extinction A_v can be derived from

$$A_v = R\{(B - V) - (B - V)_0\}. \tag{2}$$

For R we take the value 3.1.

The intrinsic color $(B\text{-}V)_0$ follows directly from the MK calibration, if the MK type is known. In addition, $(B\text{-}V)_0$ can also be derived from the UBV and β data. The distance moduli are then given by

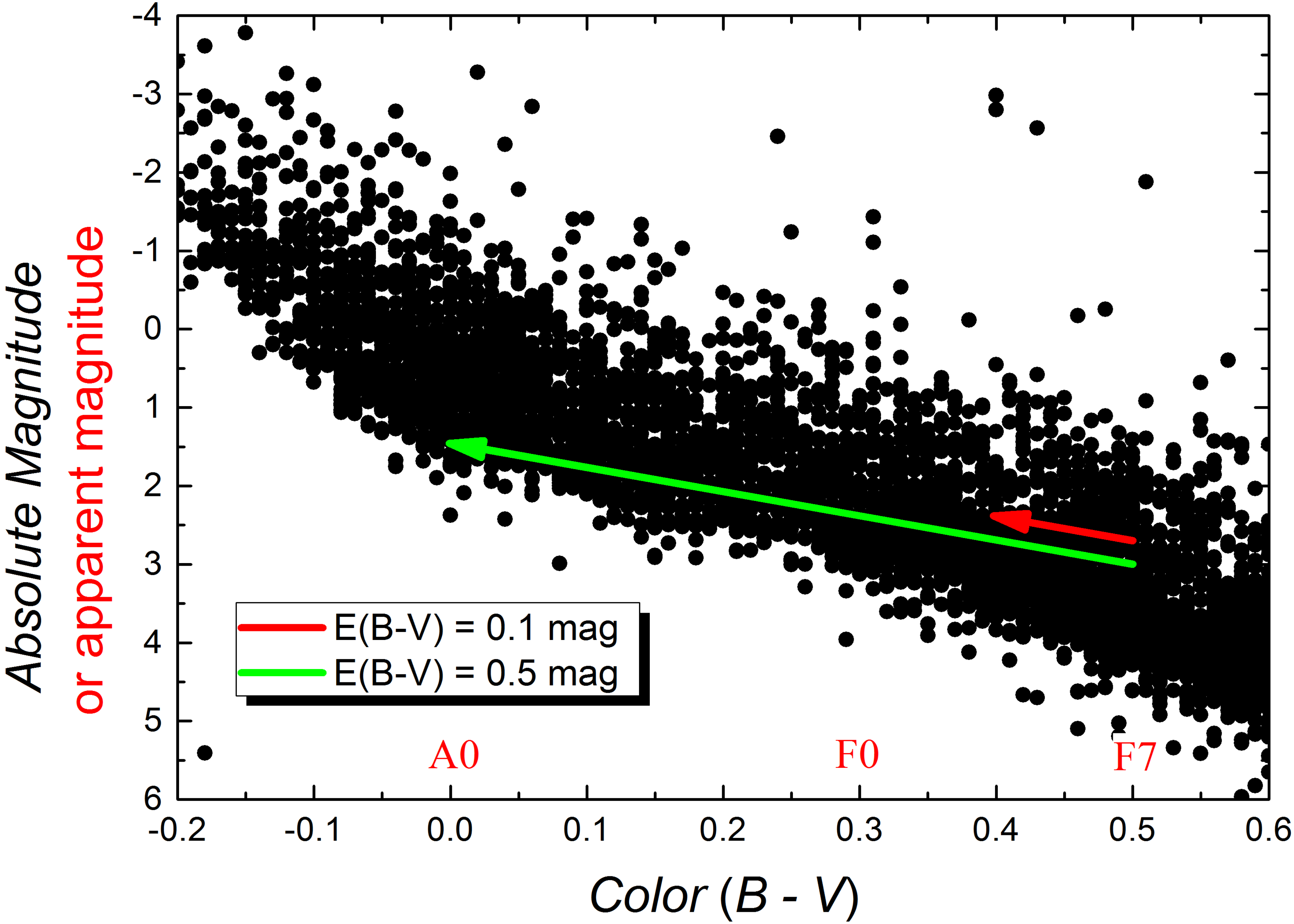
$$V - M_v - A_v = 5 \lg r - 5. \tag{3}$$

If we could derive A_v and r by both methods, we could use the mean values of extinction and distance moduli. This was possible for 1 020 stars. Figure 4 shows the frequency distribution of the differences

$$D = (V - M_v(\mathrm{MK}) - A_v(UBV, \mathrm{MK})) - \\ - (V - M_v(\beta) - A_v(UBV, \beta)). \tag{4}$$

Distance modulus

- Apparent DM: $(V - M_V)$ which still includes the reddening
- Absolute DM: $(V - M_V)_0$ or $(V_0 - M_V)$ which not includes the reddening
- Be careful there is always a mixture in the literature!


Absolute Magnitude
or apparent magnitude
Color (B - V)
E(B-V) = 0.1 mag
E(B-V) = 0.5 mag
A0
F0
F7
-4
-3
-2
-1
0
1
2
3
4
5
6
-0.2
-0.1
0.0
0.1
0.2
0.3
0.4
0.5
0.6

How to determine the DM?

- Direct isochrone fitting
- Calibrate M_V directly via photometry and spectroscopy with known reddening and V magnitude => distance directly
- Advantage: statistical sample

Guerrero et al., 2011, RMxAA, 47, 185

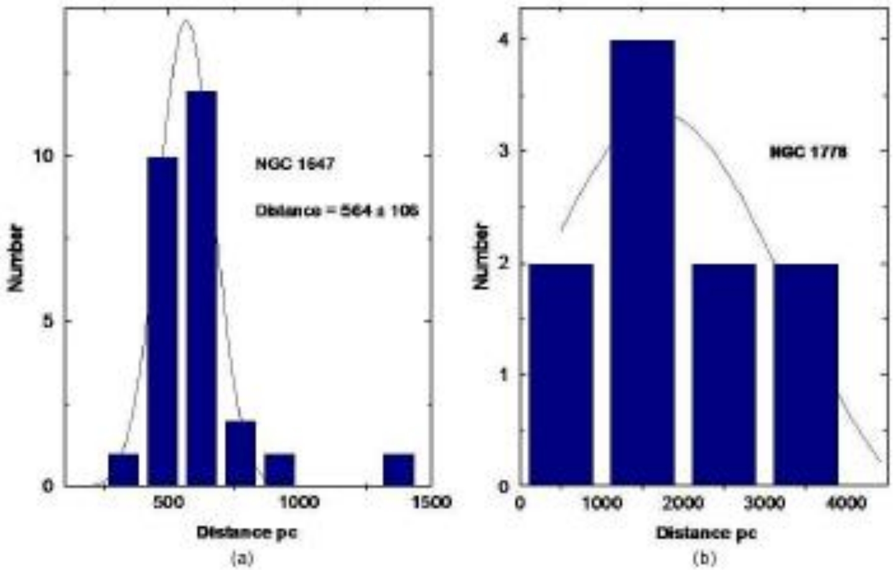


Fig. 3. Histogram of the distances for the stars in the direction of (a) NGC 1647 and (b) NGC 1778. The thin line is a Gaussian fit to the data.

Balaguer-Núñez et al., 2007, A&A, 470, 585

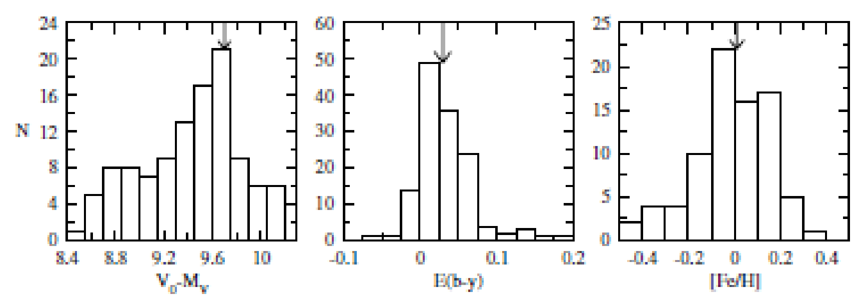


Fig. 9. The histograms of the distance modulus, reddening and metallicity of the selected member stars of M 67 with H_β measurements. The arrows indicate the mean values adopted for the cluster.