The cluster parameters

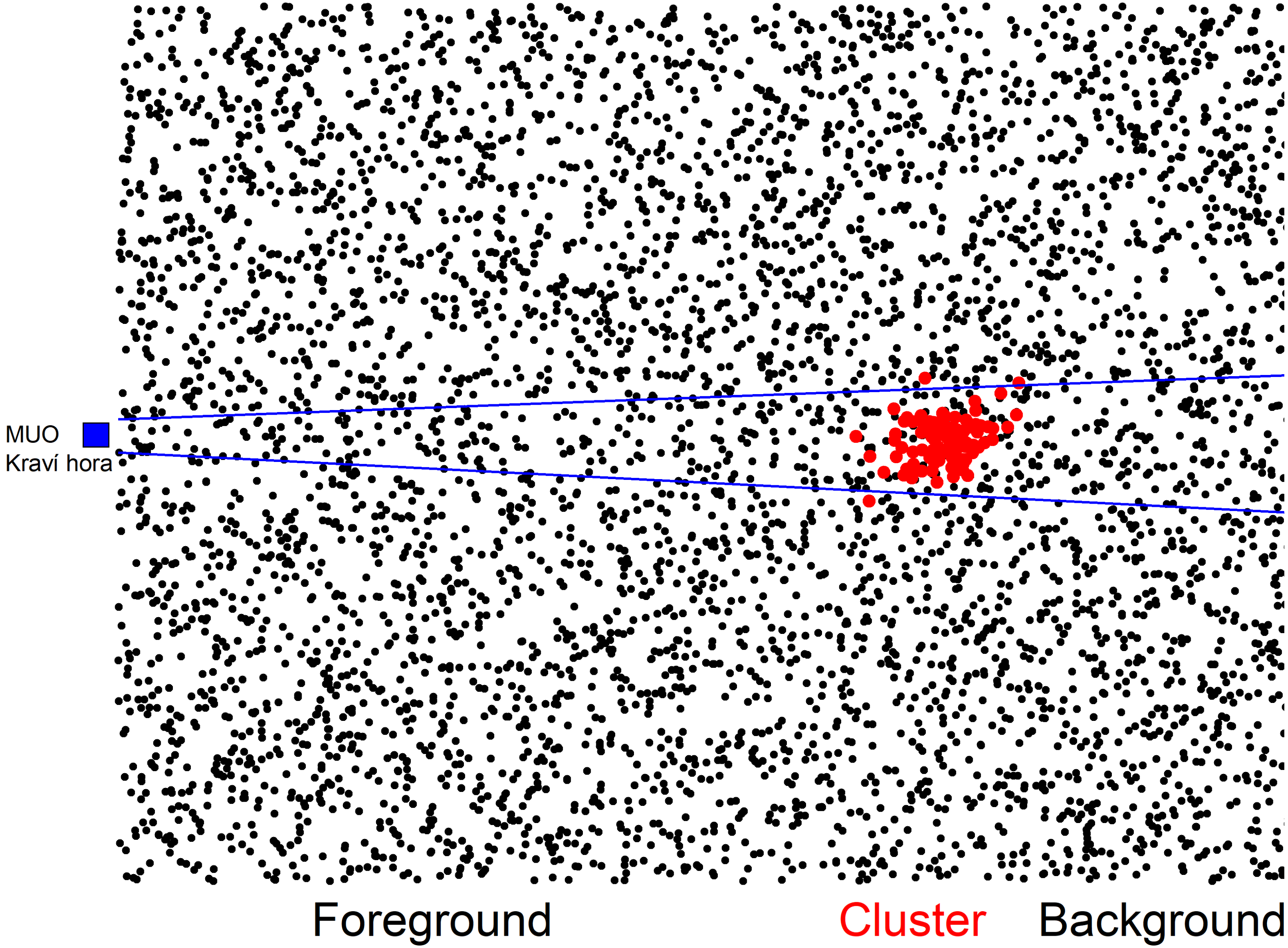
1. Reddening
2. Distance modulus
3. Age
4. Metallicity

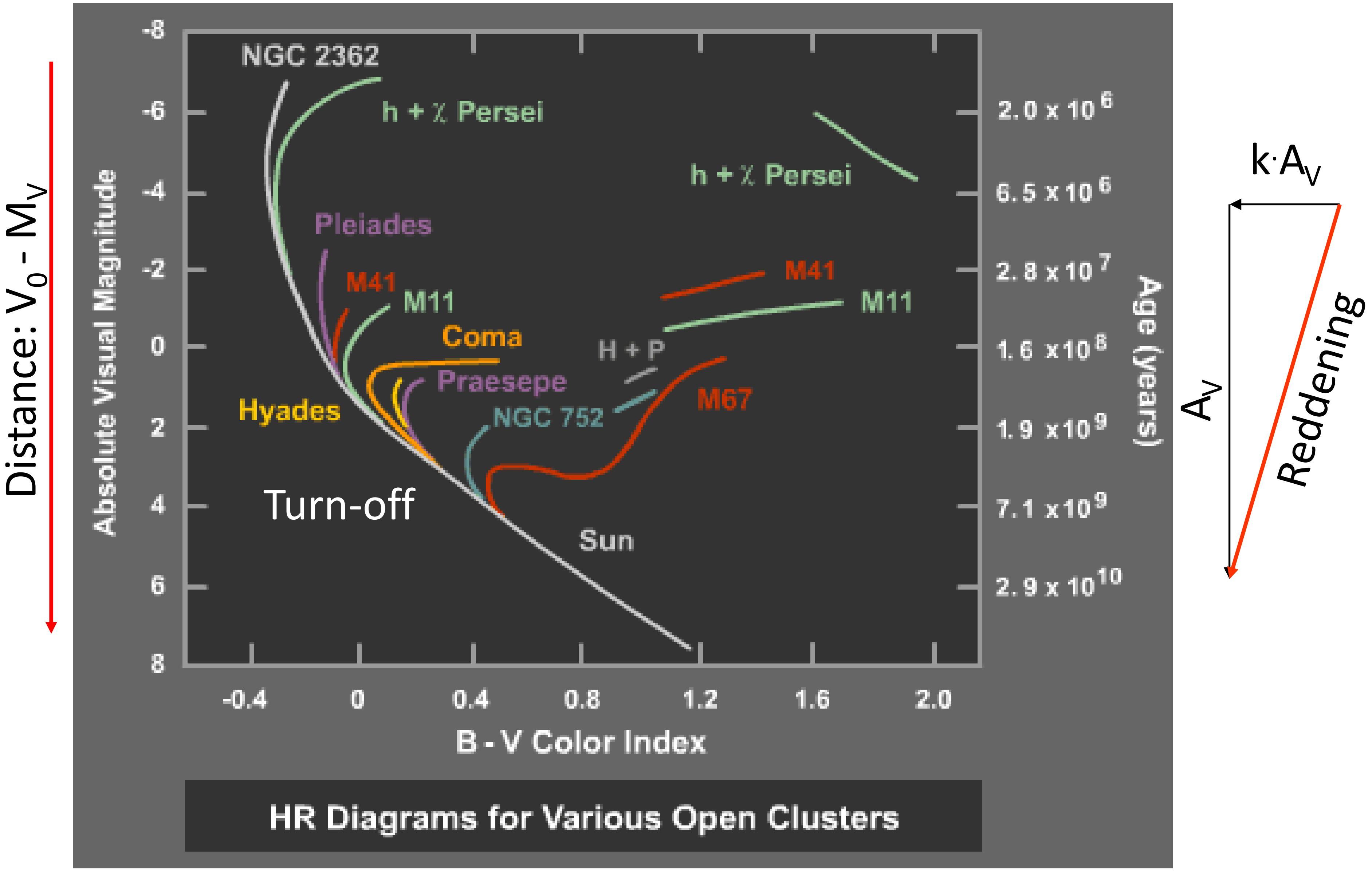
Determination in the order: Reddening, age, distance modulus simultaneously, metallicity with possible iterations

Star Clusters – tricky to analyze

NGC
7789

Star Clusters – tricky to analyze

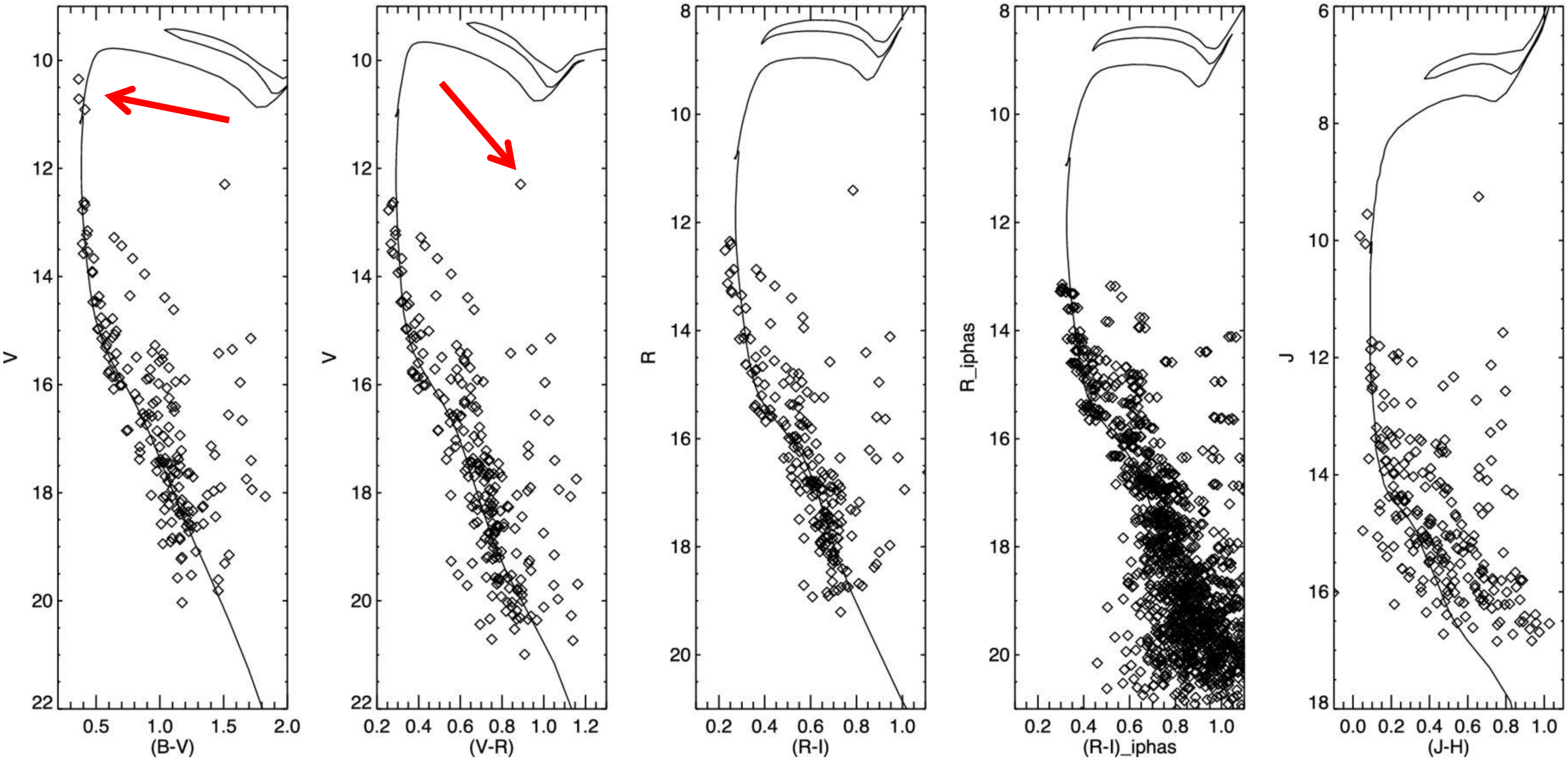




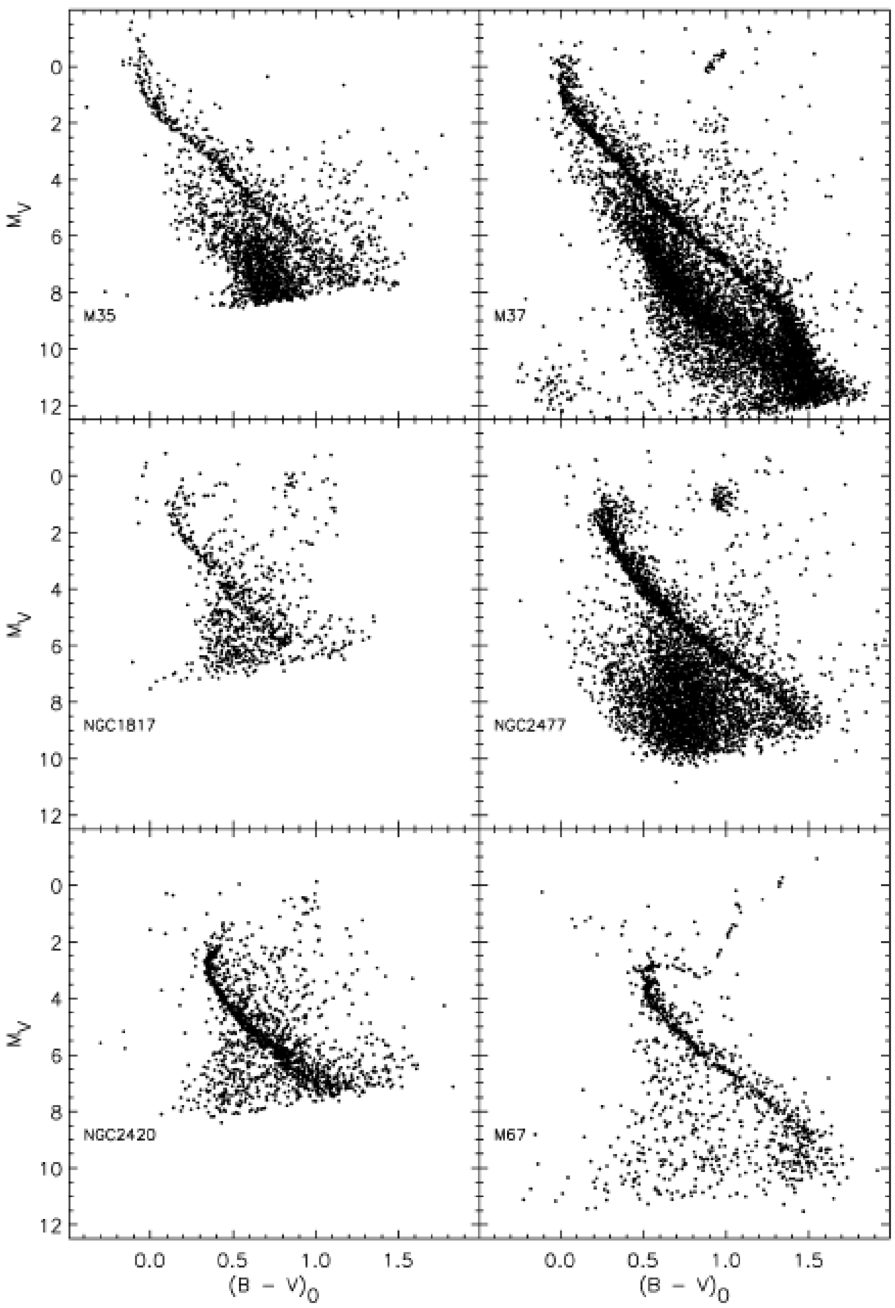
HR Diagrams for Various Open Clusters

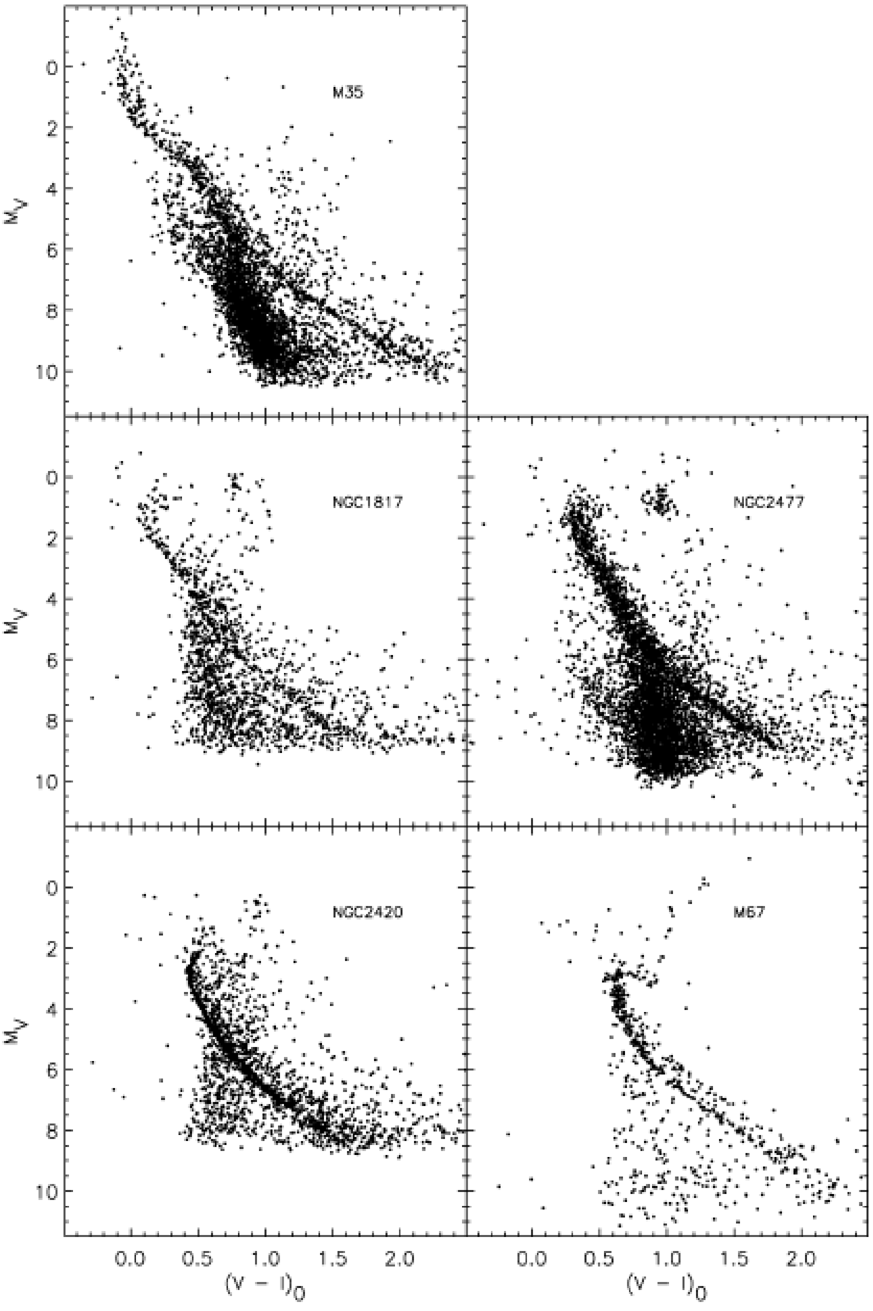
Color – Magnitude - Diagram

Different CMDs for one open cluster



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





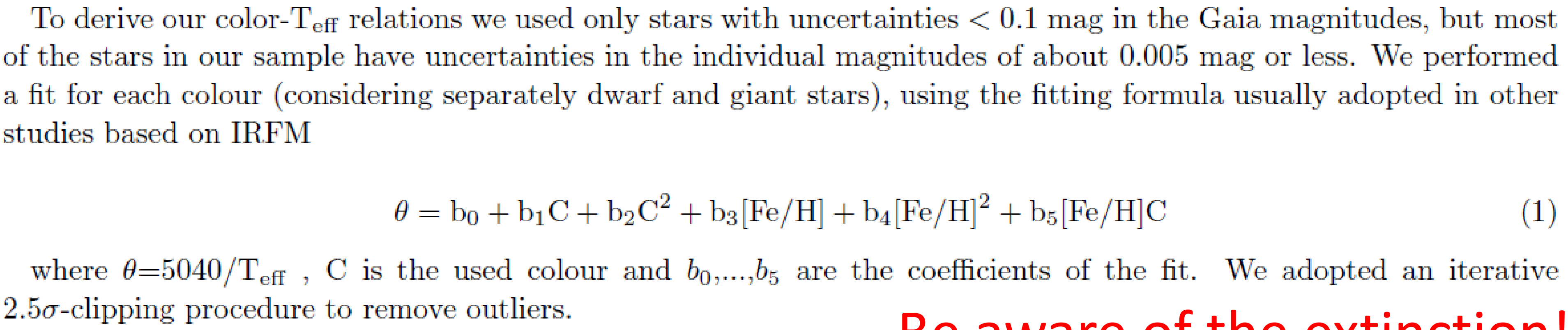
Grocholski & Sarajedini, 2003, MNRAS, 345, 1015

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. Sloan g-r, r-i, …
  4. Geneva: B2-V1, X, …
  5. Gaia: BP-RP
  6. 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, …

Photometric calibrations



To derive our color-$T_{\rm eff}$ relations we used only stars with uncertainties < 0.1 mag in the Gaia magnitudes, but most of the stars in our sample have uncertainties in the individual magnitudes of about 0.005 mag or less. We performed a fit for each colour (considering separately dwarf and giant stars), using the fitting formula usually adopted in other studies based on IRFM

$$\theta = b_0 + b_1 C + b_2 C^2 + b_3 [Fe/H] + b_4 [Fe/H]^2 + b_5 [Fe/H] C \qquad (1)$$

where θ=5040/$T_{\rm eff}$, C is the used colour and b_0,...,b_5 are the coefficients of the fit. We adopted an iterative 2.5σ-clipping procedure to remove outliers.

Be aware of the extinction!

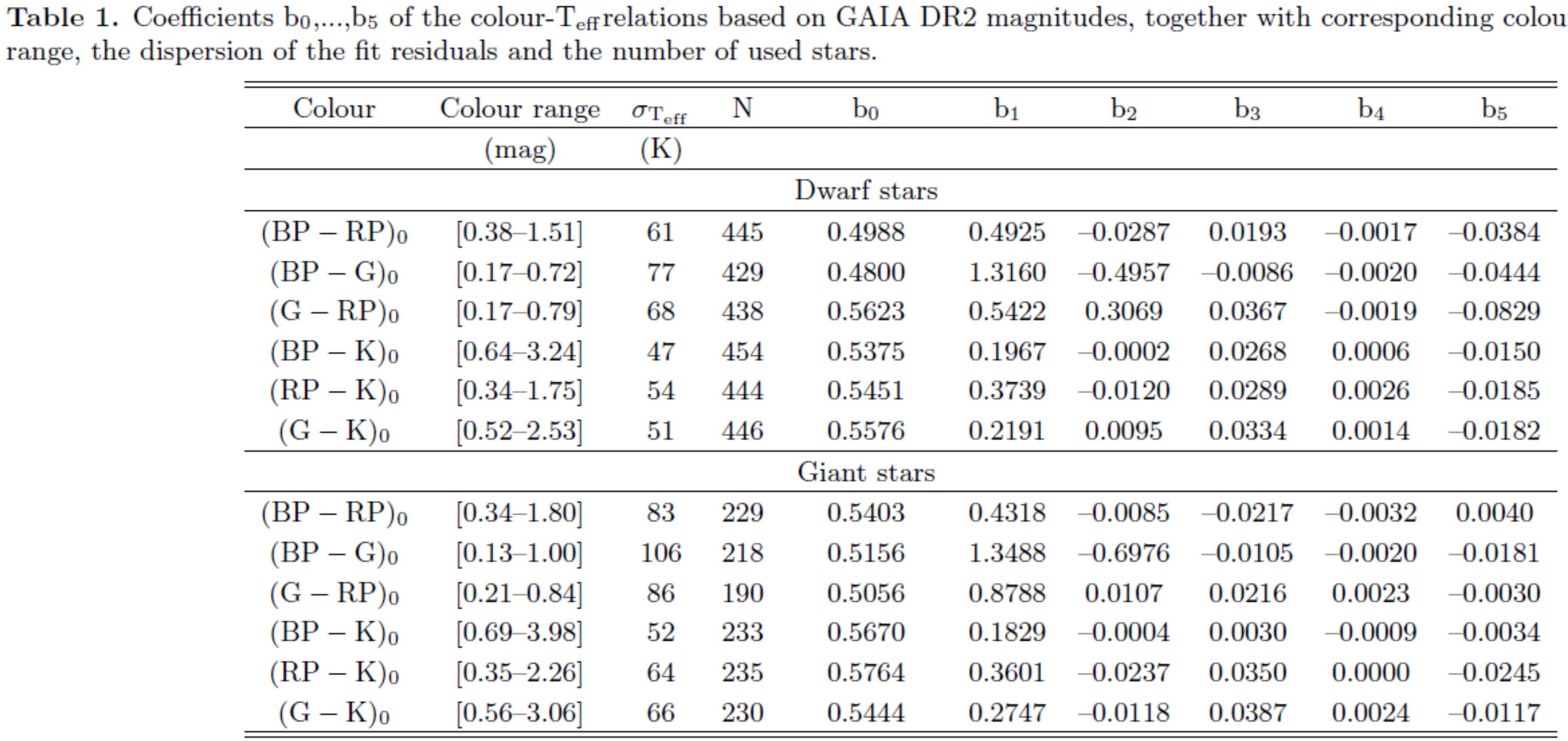


Table 1. Coefficients b_0,...,b_5 of the colour-$T_{\rm eff}$relations based on GAIA DR2 magnitudes, together with corresponding colour range, the dispersion of the fit residuals and the number of used stars.

Colour	Colour range (mag)	$\sigma_{T_{\rm eff}}$ (K)	N	b_0	b_1	b_2	b_3	b_4	b_5
				Dwarf stars					
$(BP-RP)_0$	[0.38–1.51]	61	445	0.4988	0.4925	–0.0287	0.0193	–0.0017	–0.0384
$(BP-G)_0$	[0.17–0.72]	77	429	0.4800	1.3160	–0.4957	–0.0086	–0.0020	–0.0444
$(G-RP)_0$	[0.17–0.79]	68	438	0.5623	0.5422	0.3069	0.0367	–0.0019	–0.0829
$(BP-K)_0$	[0.64–3.24]	47	454	0.5375	0.1967	–0.0002	0.0268	0.0006	–0.0150
$(RP-K)_0$	[0.34–1.75]	54	444	0.5451	0.3739	–0.0120	0.0289	0.0026	–0.0185
$(G-K)_0$	[0.52–2.53]	51	446	0.5576	0.2191	0.0095	0.0334	0.0014	–0.0182
				Giant stars					
$(BP-RP)_0$	[0.34–1.80]	83	229	0.5403	0.4318	–0.0085	–0.0217	–0.0032	0.0040
$(BP-G)_0$	[0.13–1.00]	106	218	0.5156	1.3488	–0.6976	–0.0105	–0.0020	–0.0181
$(G-RP)_0$	[0.21–0.84]	86	190	0.5056	0.8788	0.0107	0.0216	0.0023	–0.0030
$(BP-K)_0$	[0.69–3.98]	52	233	0.5670	0.1829	–0.0004	0.0030	–0.0009	–0.0034
$(RP-K)_0$	[0.35–2.26]	64	235	0.5764	0.3601	–0.0237	0.0350	0.0000	–0.0245
$(G-K)_0$	[0.56–3.06]	66	230	0.5444	0.2747	–0.0118	0.0387	0.0024	–0.0117

Mucciarelli & Bellazzini, 2020, Research Notes of the AAS, 4, 52

Photometric calibrations

Empirical photometric calibration of the *Gaia* red clump: Colours, effective temperature, and absolute magnitude★

L. Ruiz-Dern, C. Babusiaux, F. Arenou, C. Turon, and R. Lallement

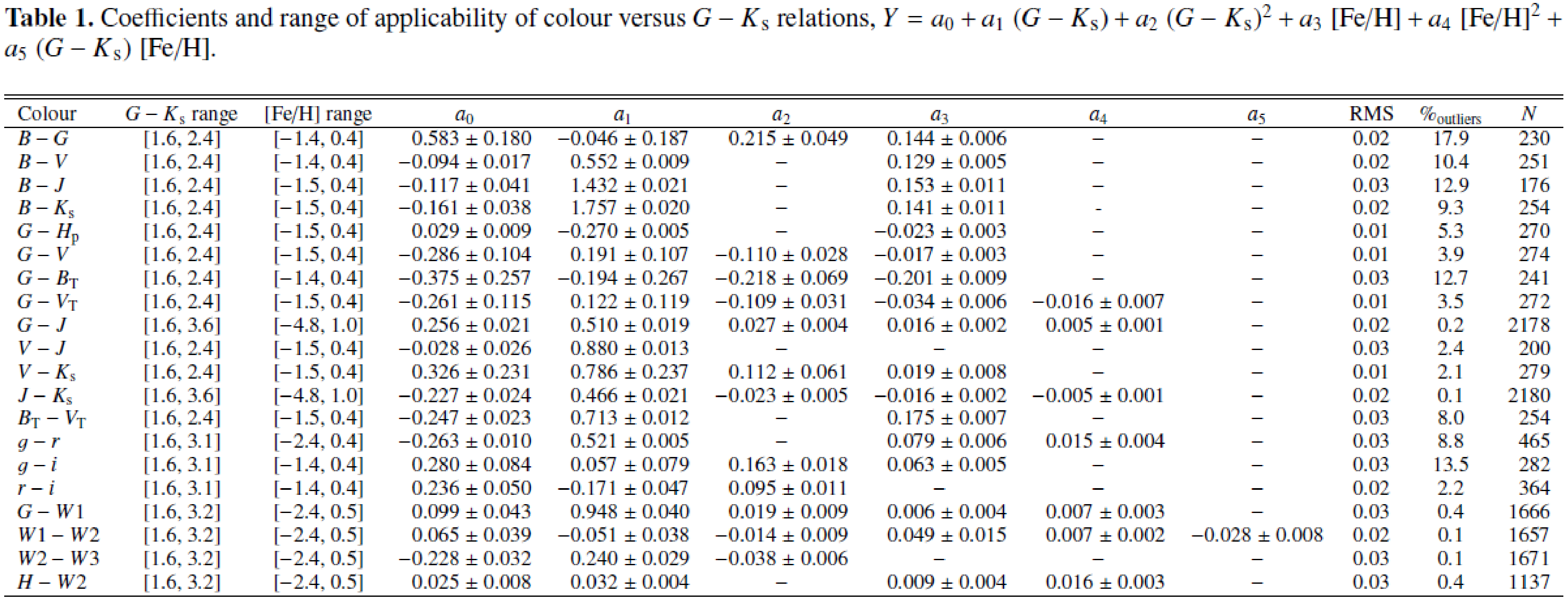
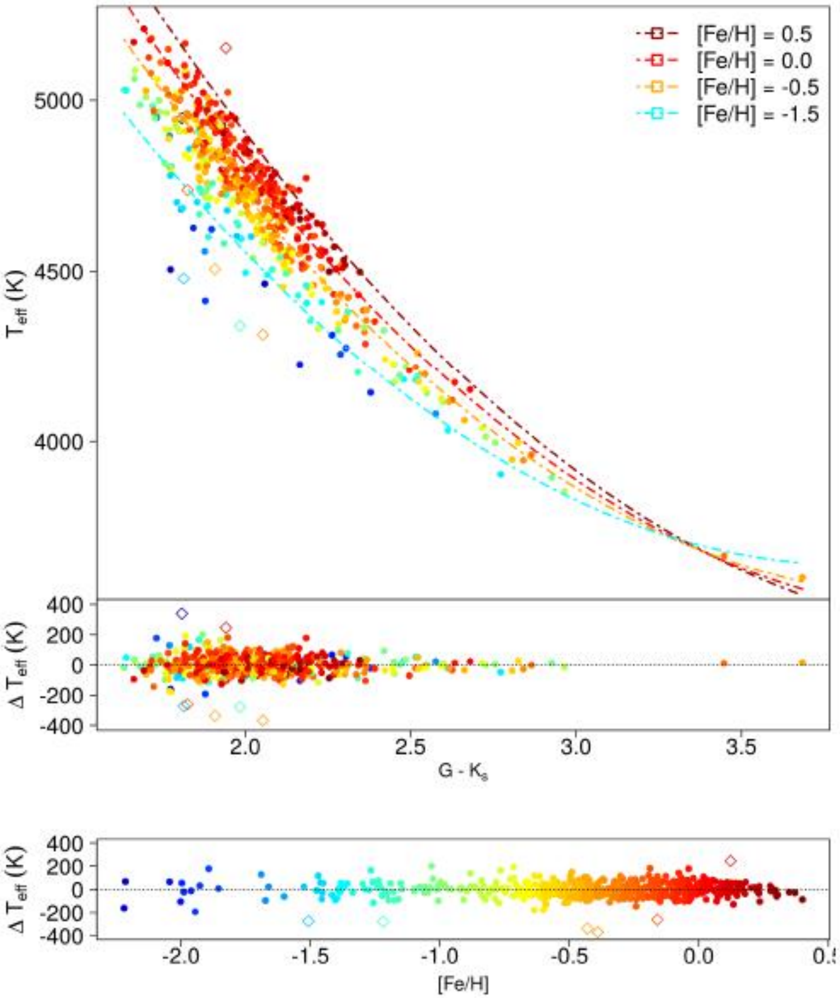


Table 1. Coefficients and range of applicability of colour versus $G - K_s$ relations, $Y = a_0 + a_1\,(G - K_s) + a_2\,(G - K_s)^2 + a_3\,[\mathrm{Fe/H}] + a_4\,[\mathrm{Fe/H}]^2 + a_5\,(G - K_s)\,[\mathrm{Fe/H}]$.

Colour	$G - K_s$ range	[Fe/H] range	a_0	a_1	a_2	a_3	a_4	a_5	RMS	$\%_{\mathrm{outliers}}$	N
$B - G$	[1.6, 2.4]	[−1.4, 0.4]	0.583 ± 0.180	−0.046 ± 0.187	0.215 ± 0.049	0.144 ± 0.006	–	–	0.02	17.9	230
$B - V$	[1.6, 2.4]	[−1.4, 0.4]	−0.094 ± 0.017	0.552 ± 0.009	–	0.129 ± 0.005	–	–	0.02	10.4	251
$B - J$	[1.6, 2.4]	[−1.5, 0.4]	−0.117 ± 0.041	1.432 ± 0.021	–	0.153 ± 0.011	–	–	0.03	12.9	176
$B - K_s$	[1.6, 2.4]	[−1.5, 0.4]	−0.161 ± 0.038	1.757 ± 0.020	–	0.141 ± 0.011	-	–	0.02	9.3	254
$G - H_p$	[1.6, 2.4]	[−1.5, 0.4]	0.029 ± 0.009	−0.270 ± 0.005	–	−0.023 ± 0.003	–	–	0.01	5.3	270
$G - V$	[1.6, 2.4]	[−1.5, 0.4]	−0.286 ± 0.104	0.191 ± 0.107	−0.110 ± 0.028	−0.017 ± 0.003	–	–	0.01	3.9	274
$G - B_T$	[1.6, 2.4]	[−1.4, 0.4]	−0.375 ± 0.257	−0.194 ± 0.267	−0.218 ± 0.069	−0.201 ± 0.009	–	–	0.03	12.7	241
$G - V_T$	[1.6, 2.4]	[−1.5, 0.4]	−0.261 ± 0.115	0.122 ± 0.119	−0.109 ± 0.031	−0.034 ± 0.006	−0.016 ± 0.007	–	0.01	3.5	272
$G - J$	[1.6, 3.6]	[−4.8, 1.0]	0.256 ± 0.021	0.510 ± 0.019	0.027 ± 0.004	0.016 ± 0.002	0.005 ± 0.001	–	0.02	0.2	2178
$V - J$	[1.6, 2.4]	[−1.5, 0.4]	−0.028 ± 0.026	0.880 ± 0.013	–	–	–	–	0.03	2.4	200
$V - K_s$	[1.6, 2.4]	[−1.5, 0.4]	0.326 ± 0.231	0.786 ± 0.237	0.112 ± 0.061	0.019 ± 0.008	–	–	0.01	2.1	279
$J - K_s$	[1.6, 3.6]	[−4.8, 1.0]	−0.227 ± 0.024	0.466 ± 0.021	−0.023 ± 0.005	−0.016 ± 0.002	−0.005 ± 0.001	–	0.02	0.1	2180
$B_T - V_T$	[1.6, 2.4]	[−1.5, 0.4]	−0.247 ± 0.023	0.713 ± 0.012	–	0.175 ± 0.007	–	–	0.03	8.0	254
$g - r$	[1.6, 3.1]	[−2.4, 0.4]	−0.263 ± 0.010	0.521 ± 0.005	–	0.079 ± 0.006	0.015 ± 0.004	–	0.03	8.8	465
$g - i$	[1.6, 3.1]	[−1.4, 0.4]	0.280 ± 0.084	0.057 ± 0.079	0.163 ± 0.018	0.063 ± 0.005	–	–	0.03	13.5	282
$r - i$	[1.6, 3.1]	[−1.4, 0.4]	0.236 ± 0.050	−0.171 ± 0.047	0.095 ± 0.011	–	–	–	0.02	2.2	364
$G - W1$	[1.6, 3.2]	[−2.4, 0.5]	0.099 ± 0.043	0.948 ± 0.040	0.019 ± 0.009	0.006 ± 0.004	0.007 ± 0.003	–	0.03	0.4	1666
$W1 - W2$	[1.6, 3.2]	[−2.4, 0.5]	0.065 ± 0.039	−0.051 ± 0.038	−0.014 ± 0.009	0.049 ± 0.015	0.007 ± 0.002	−0.028 ± 0.008	0.02	0.1	1657
$W2 - W3$	[1.6, 3.2]	[−2.4, 0.5]	−0.228 ± 0.032	0.240 ± 0.029	−0.038 ± 0.006	–	–	–	0.03	0.1	1671
$H - W2$	[1.6, 3.2]	[−2.4, 0.5]	0.025 ± 0.008	0.032 ± 0.004	–	0.009 ± 0.004	0.016 ± 0.003	–	0.03	0.4	1137

Ruiz-Dern et al., 2018, A&A, 609, A116

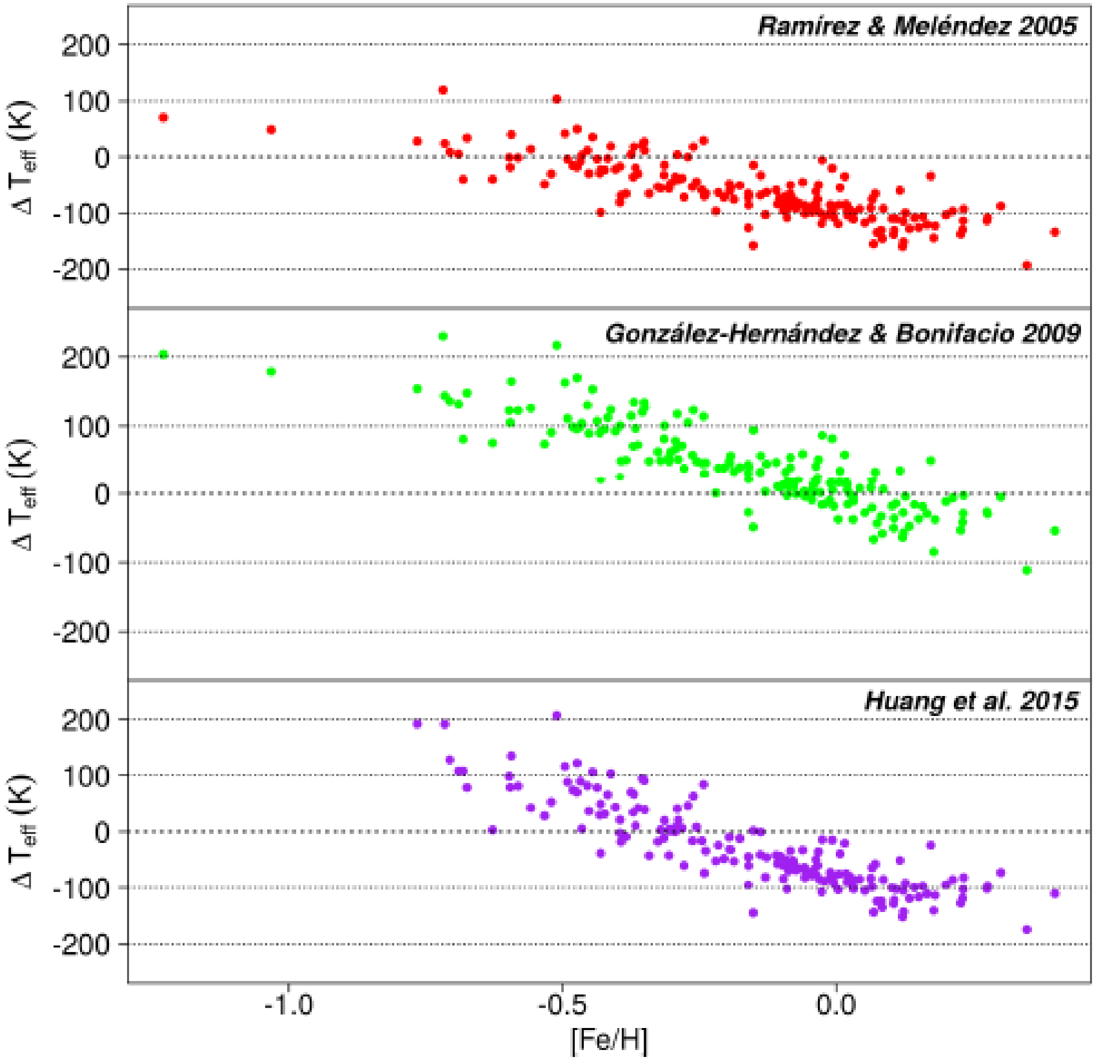
Photometric calibrations



Final calibration

Ruiz-Dern et al., 2018, A&A, 609, A116

Photometric calibrations



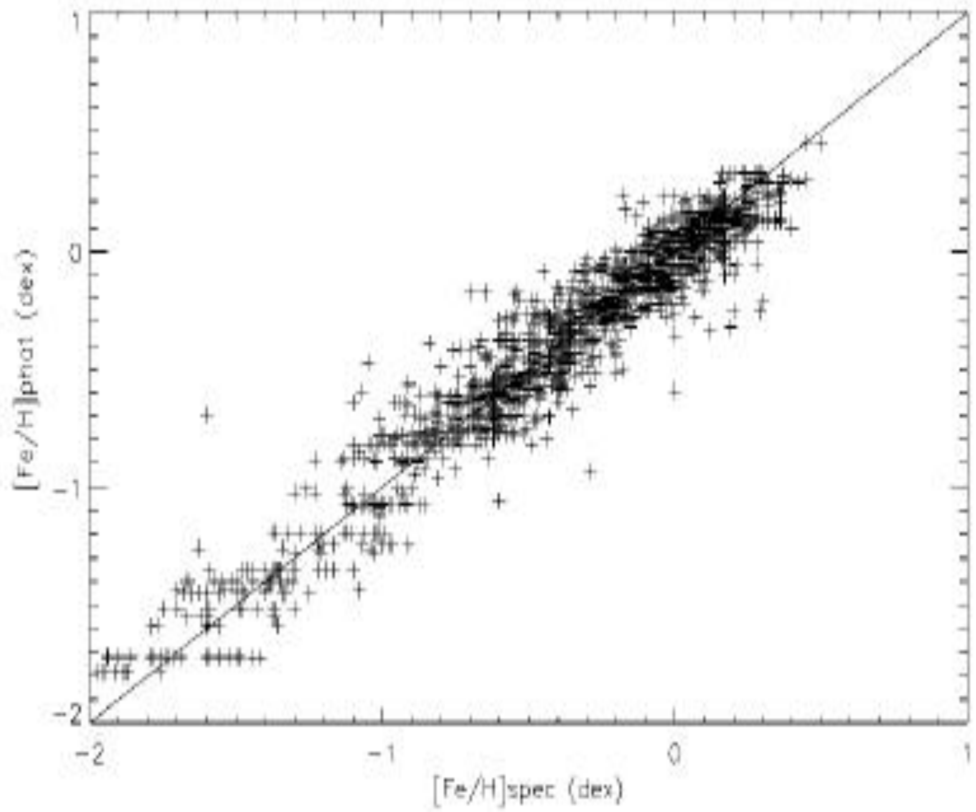
Comparison with other calibrations

Ruiz-Dern et al., 2018, A&A, 609, A116

Photometric calibrations

Error: +-0.10 dex

$$
\begin{aligned}
[\mathrm{Fe/H}]_{\mathrm{phot}} = {} & -10.424602 + 31.059003(b-y) \\
& + 42.184476 m_1 + 15.351995 c_1 \\
& - 11.239435(b-y)^2 - 29.218135 m_1^2 \\
& - 11.457610 c_1^2 - 138.92376(b-y) m_1 \\
& - 52.033290(b-y) c_1 + 11.259341 m_1 c_1 \\
& - 46.087731(b-y)^3 + 26.065099 m_1^3 \\
& - 1.1017830 c_1^3 + 138.48588(b-y)^2 m_1 \\
& + 39.012001(b-y)^2 c_1 \\
& + 23.225562 m_1^2 (b-y) - 69.146876 m_1^2 c_1 \\
& + 20.456093 c_1^2 (b-y) - 3.3302478 c_1^2 m_1 \\
& + 70.168761(b-y) m_1 c_1 .
\end{aligned}
$$



Martell & Laughlin, 2002, ApJ, 577, L45

How to derive cluster parameters?

- 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
- Automatic procedures available, but be careful

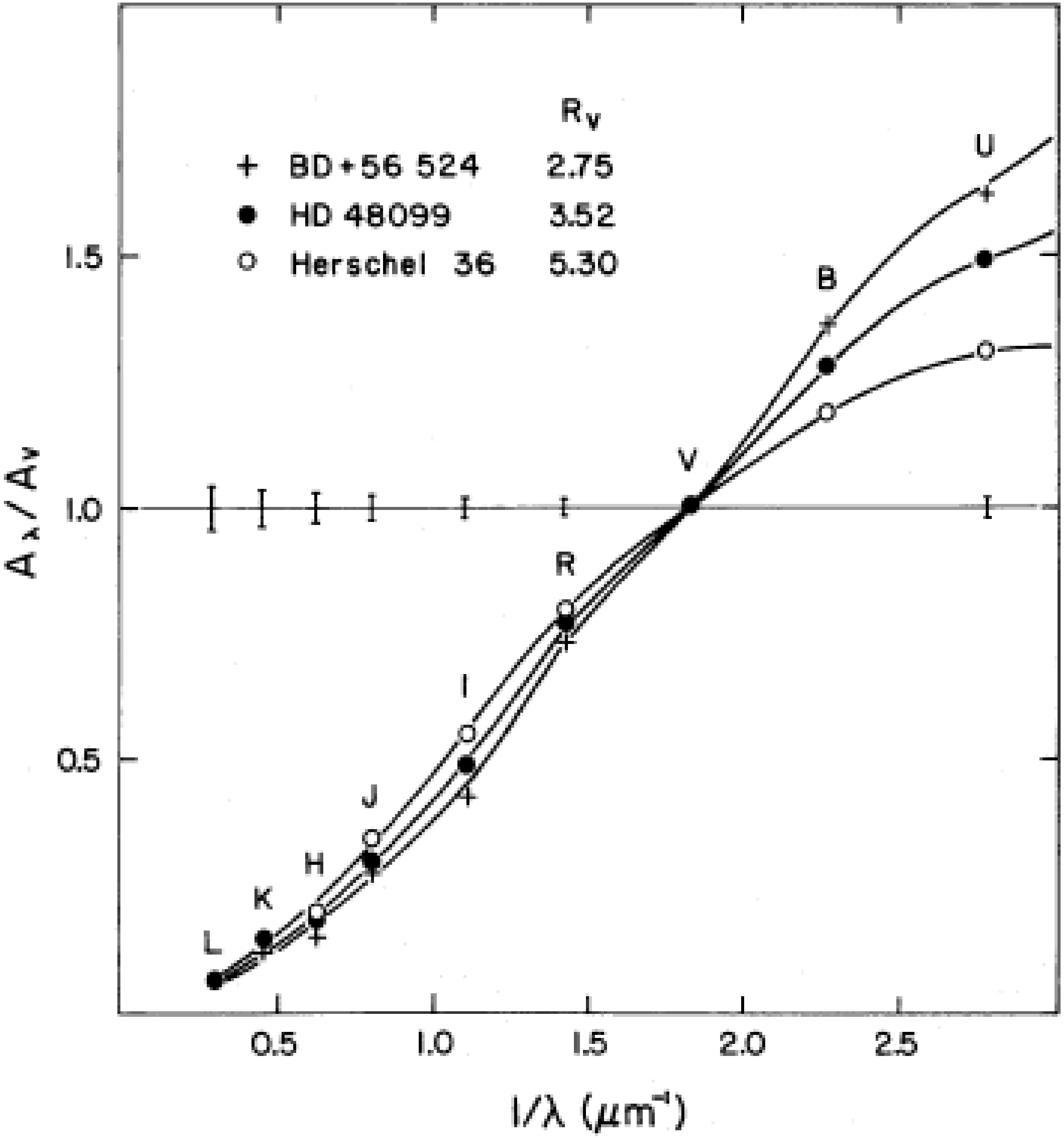
Absorption = Extinction = Reddening

- $A_V = k_1\ E(B\text{-}V) = k_2\ E(V\text{-}R) = \ldots$
- 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:

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

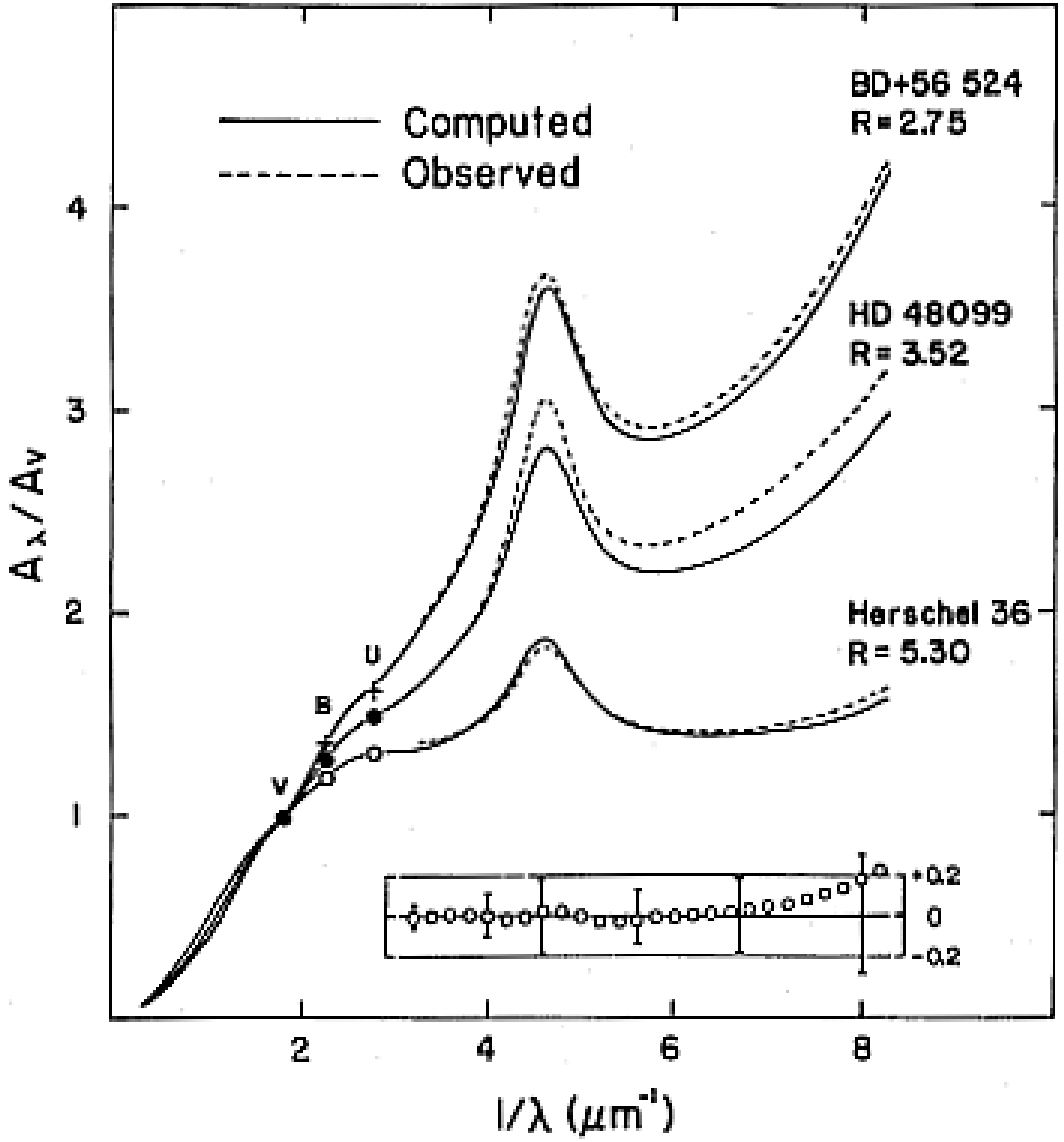
Normalization factor

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

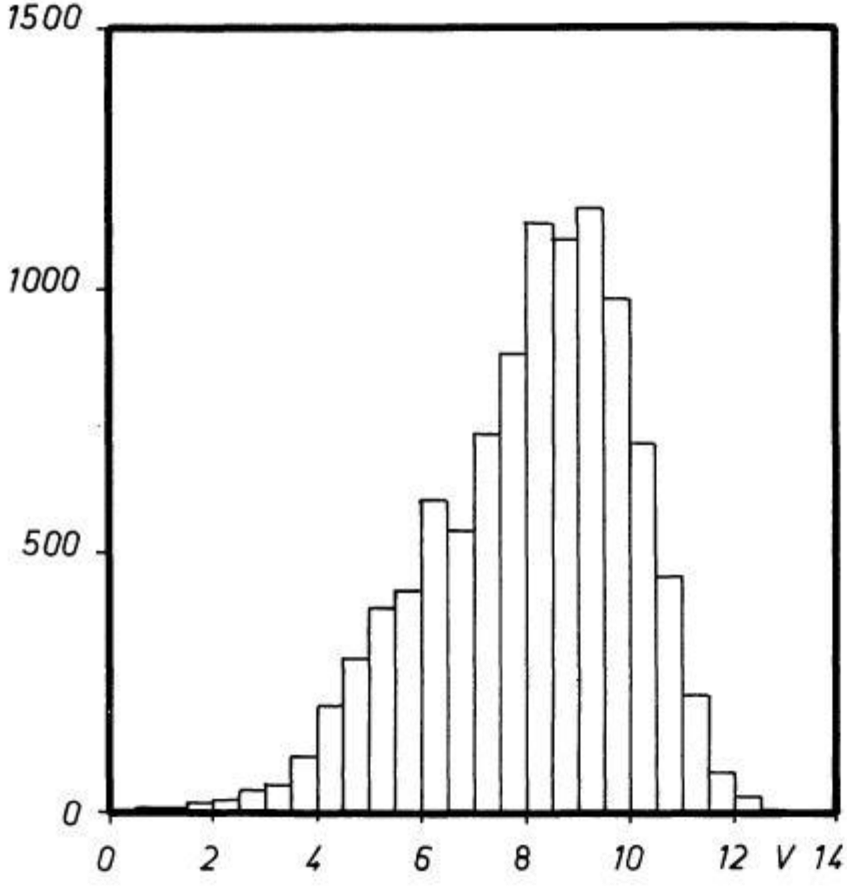


FIGURE 2. — Distribution of the stars *versus* apparent *V*-magnitude.

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

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

For R we take the value 3.1.

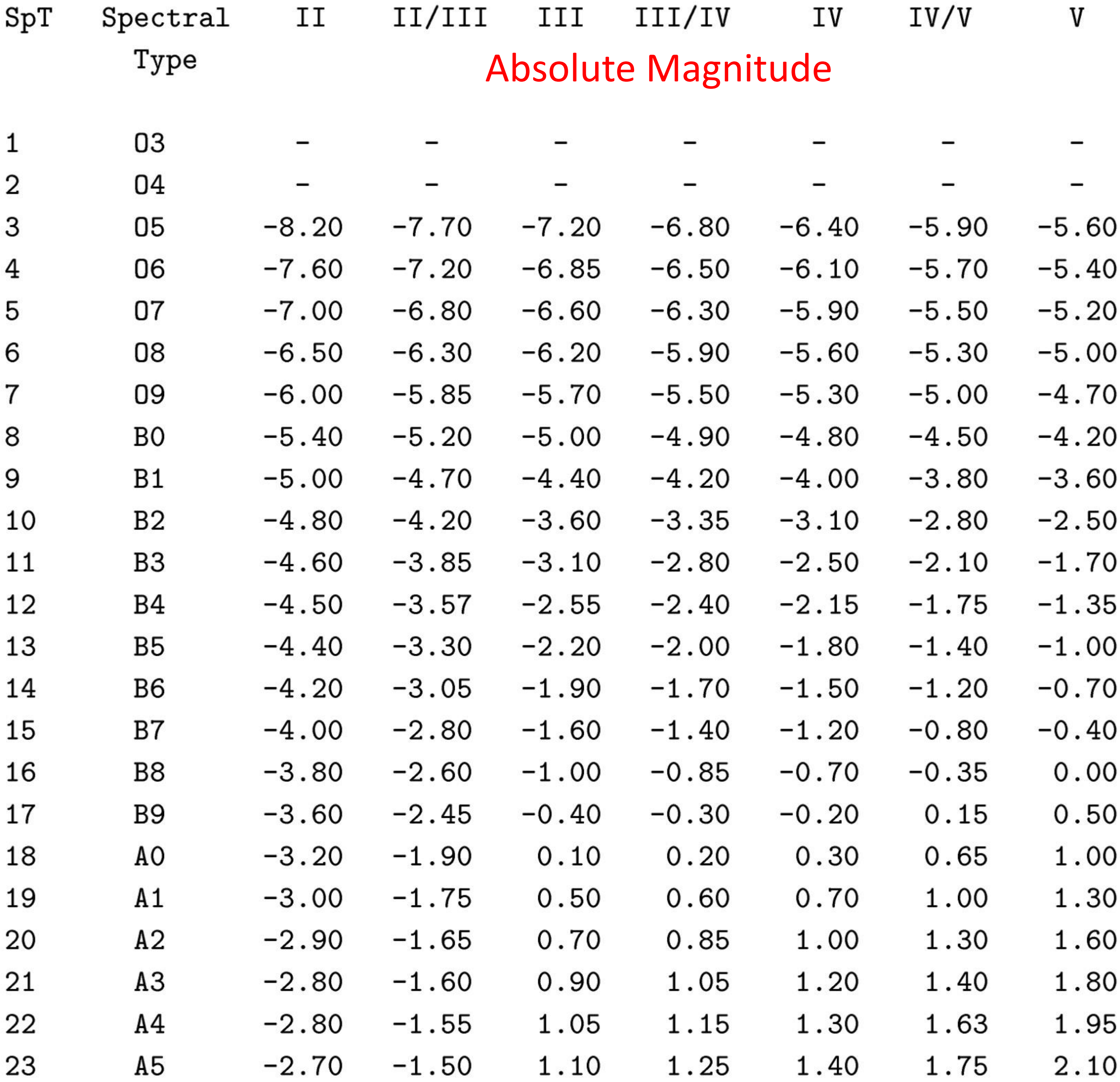
The intrinsic color $(B\text{-}V)_0$ follows directly from the MK calibration, if the MK type is known. In addition, $(B\text{-}V)_0$ can also be derived from the UBV and β data. The distance moduli are then given by

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

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

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

Bailer-Jones, 1996, PhD, Cambridge University



Absolute Magnitude

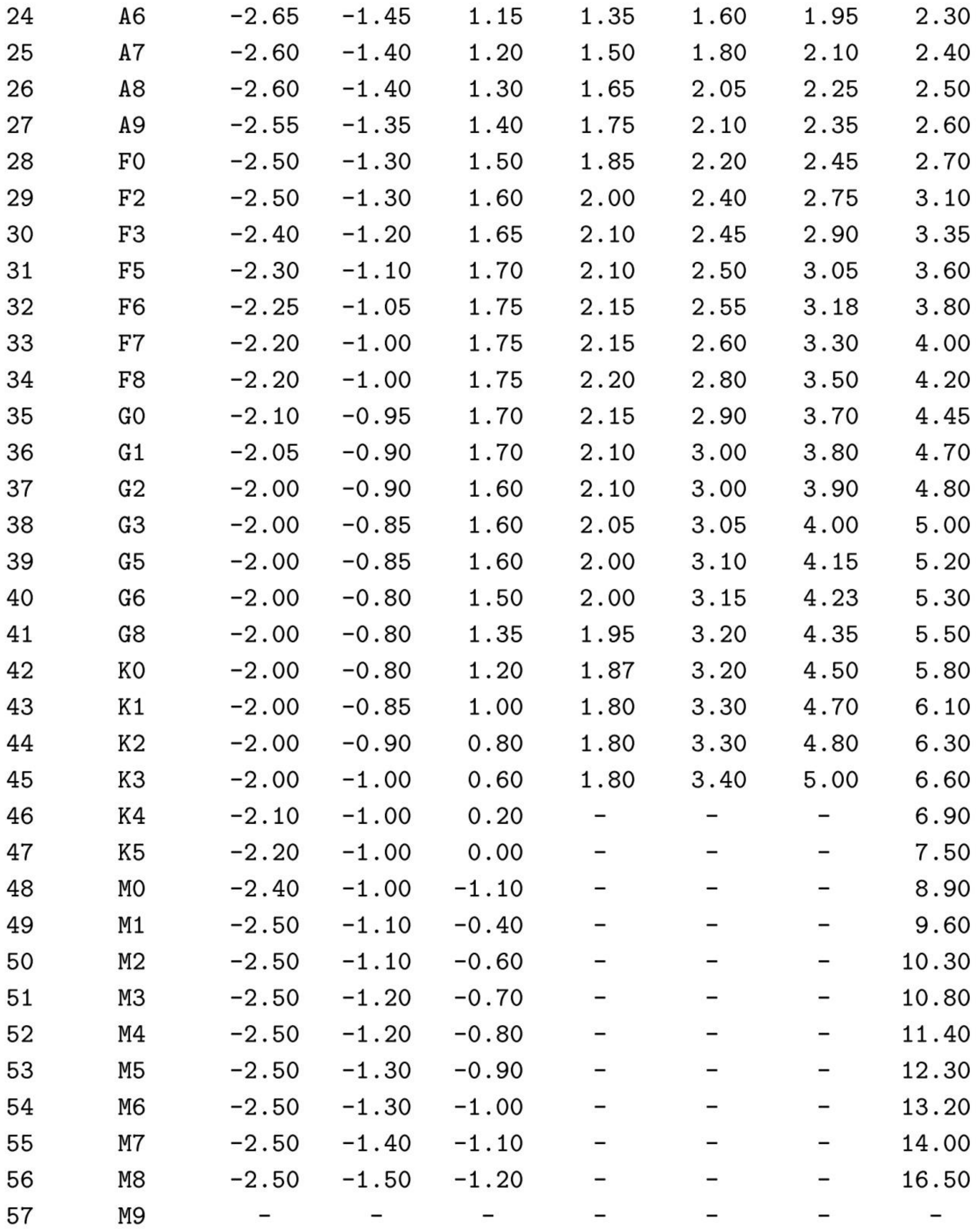
SpT	Spectral Type	II	II/III	III	III/IV	IV	IV/V	V
1	O3	-	-	-	-	-	-	-
2	O4	-	-	-	-	-	-	-
3	O5	-8.20	-7.70	-7.20	-6.80	-6.40	-5.90	-5.60
4	O6	-7.60	-7.20	-6.85	-6.50	-6.10	-5.70	-5.40
5	O7	-7.00	-6.80	-6.60	-6.30	-5.90	-5.50	-5.20
6	O8	-6.50	-6.30	-6.20	-5.90	-5.60	-5.30	-5.00
7	O9	-6.00	-5.85	-5.70	-5.50	-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	-	-	-	-	-	-	-

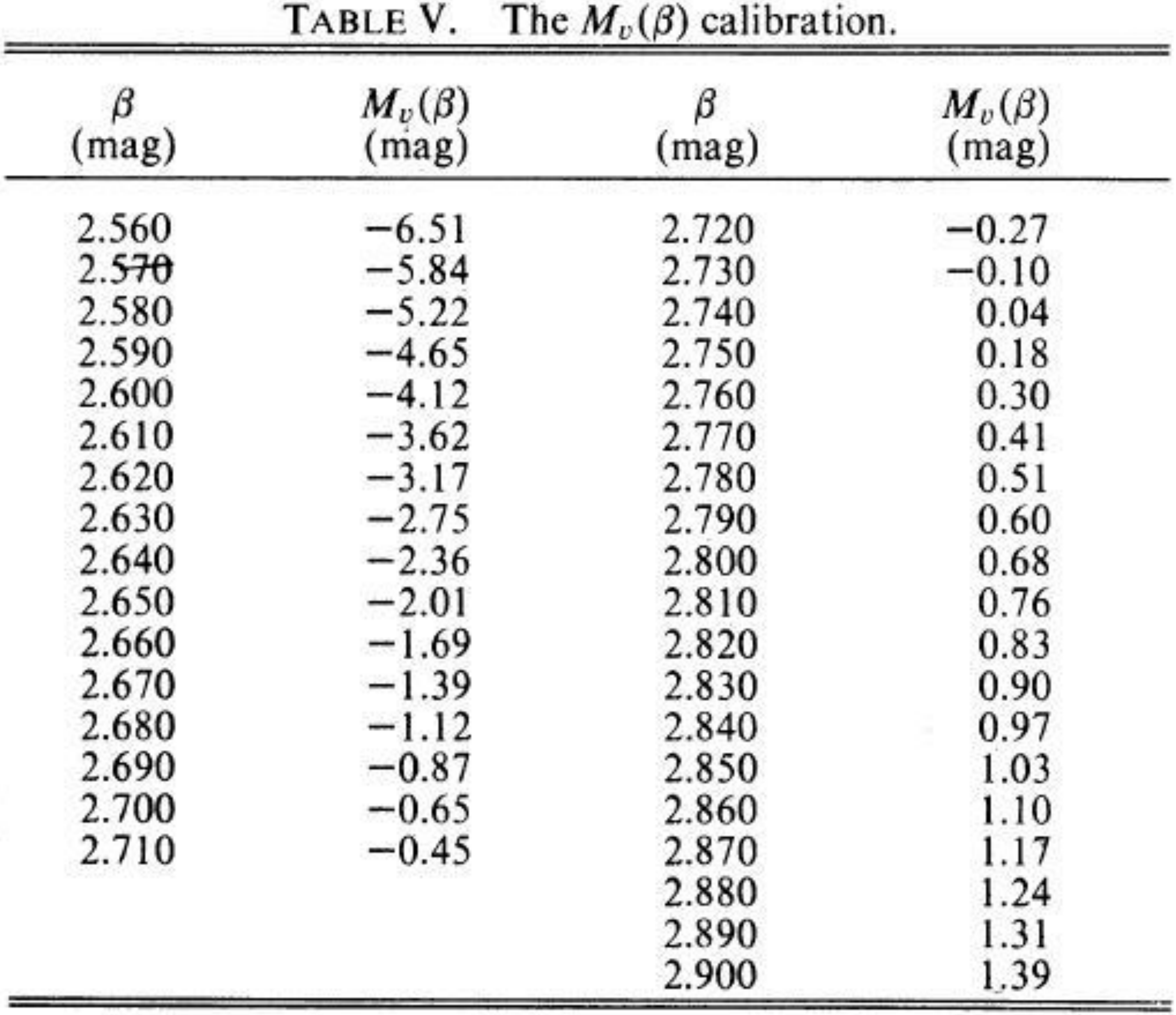


TABLE V. The $M_v(\beta)$ calibration.

β (mag)	$M_v(\beta)$ (mag)	β (mag)	$M_v(\beta)$ (mag)
2.560	−6.51	2.720	−0.27
2.5~~70~~	−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

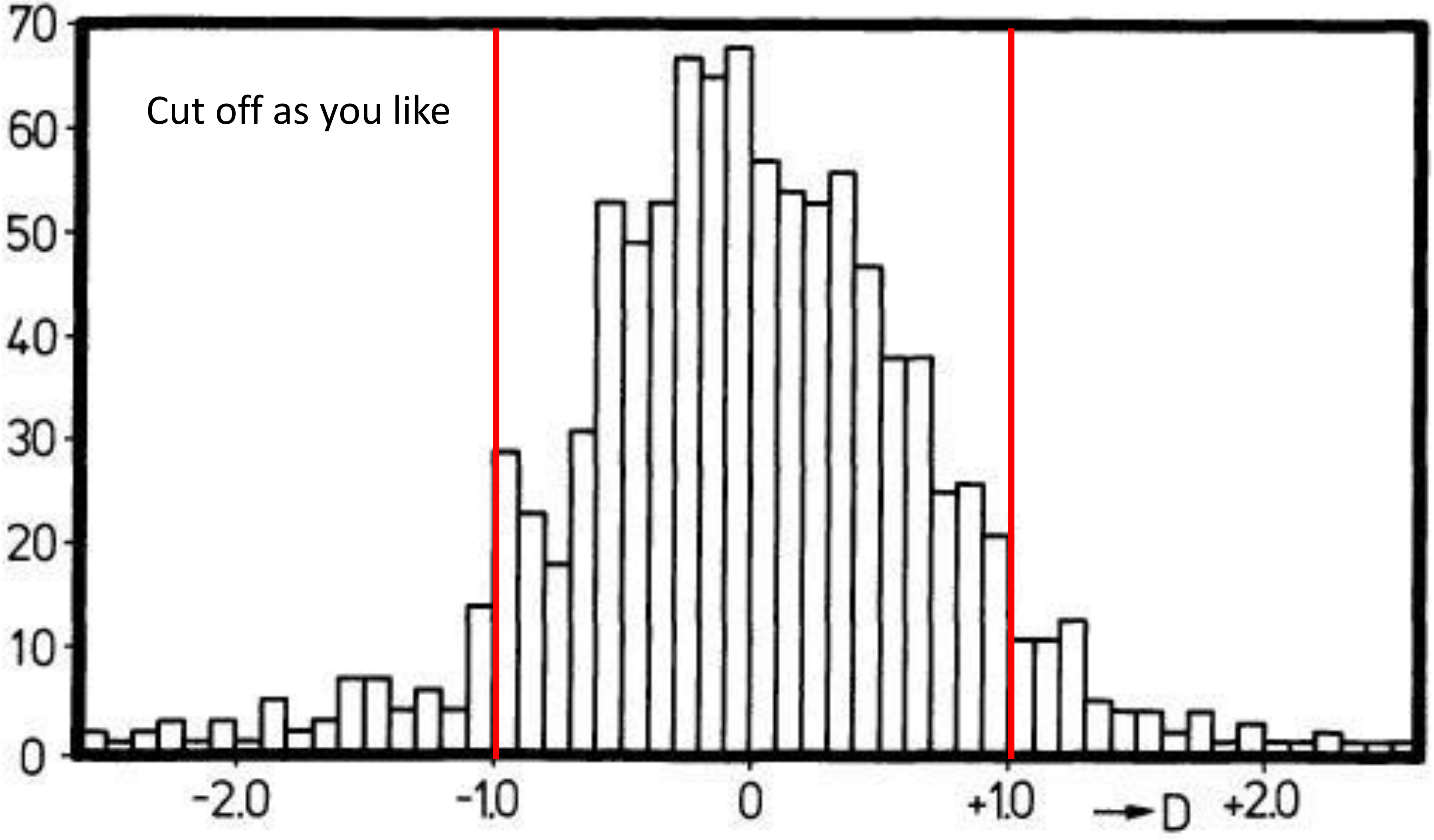
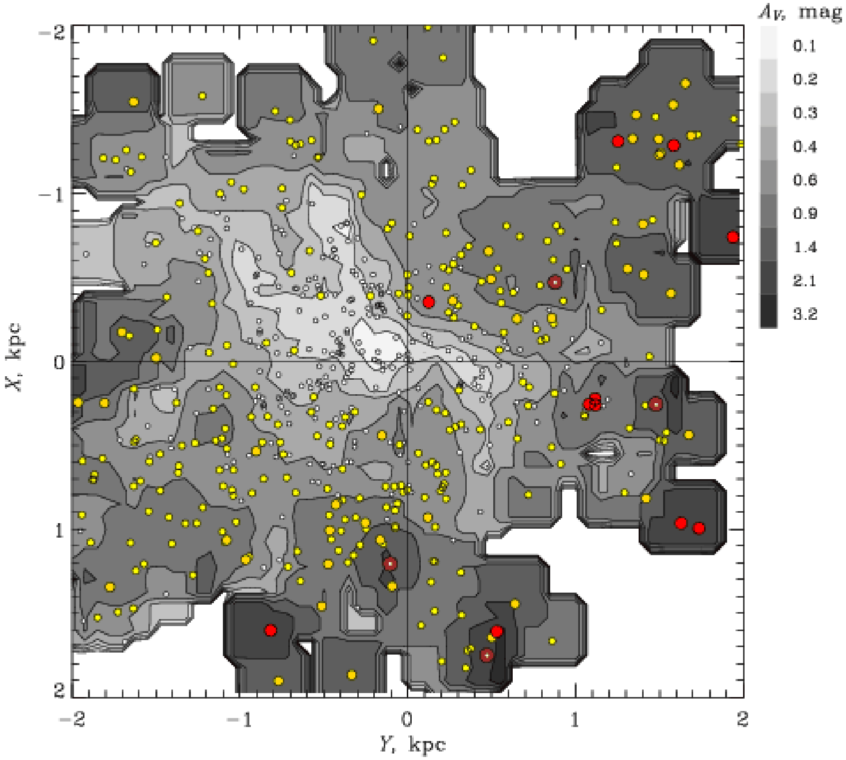
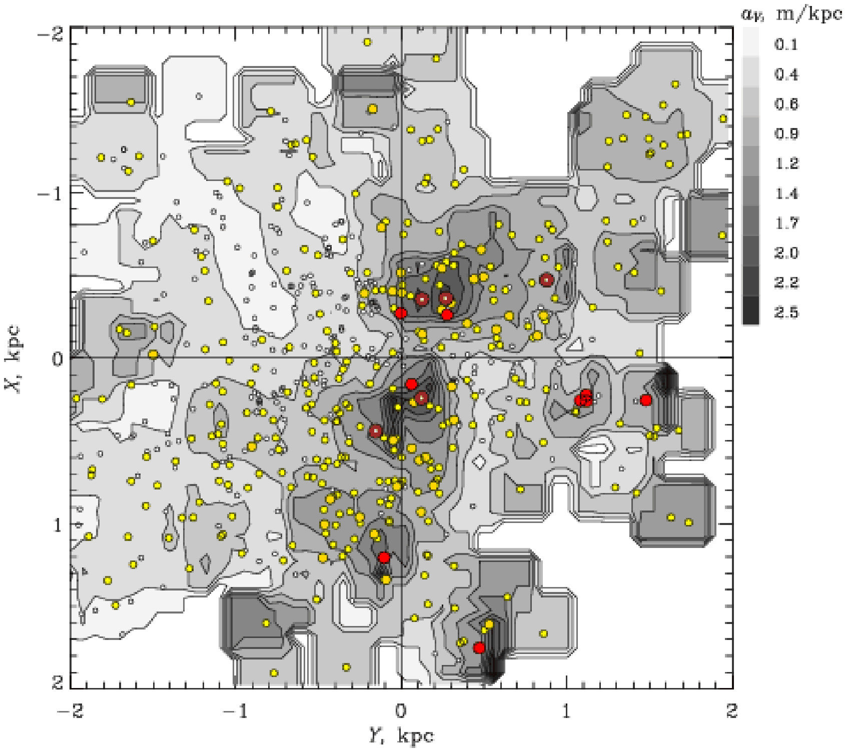

Cut off as you like

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

Reddening Maps

http://argonaut.skymaps.info/
http://www.univie.ac.at/p2f





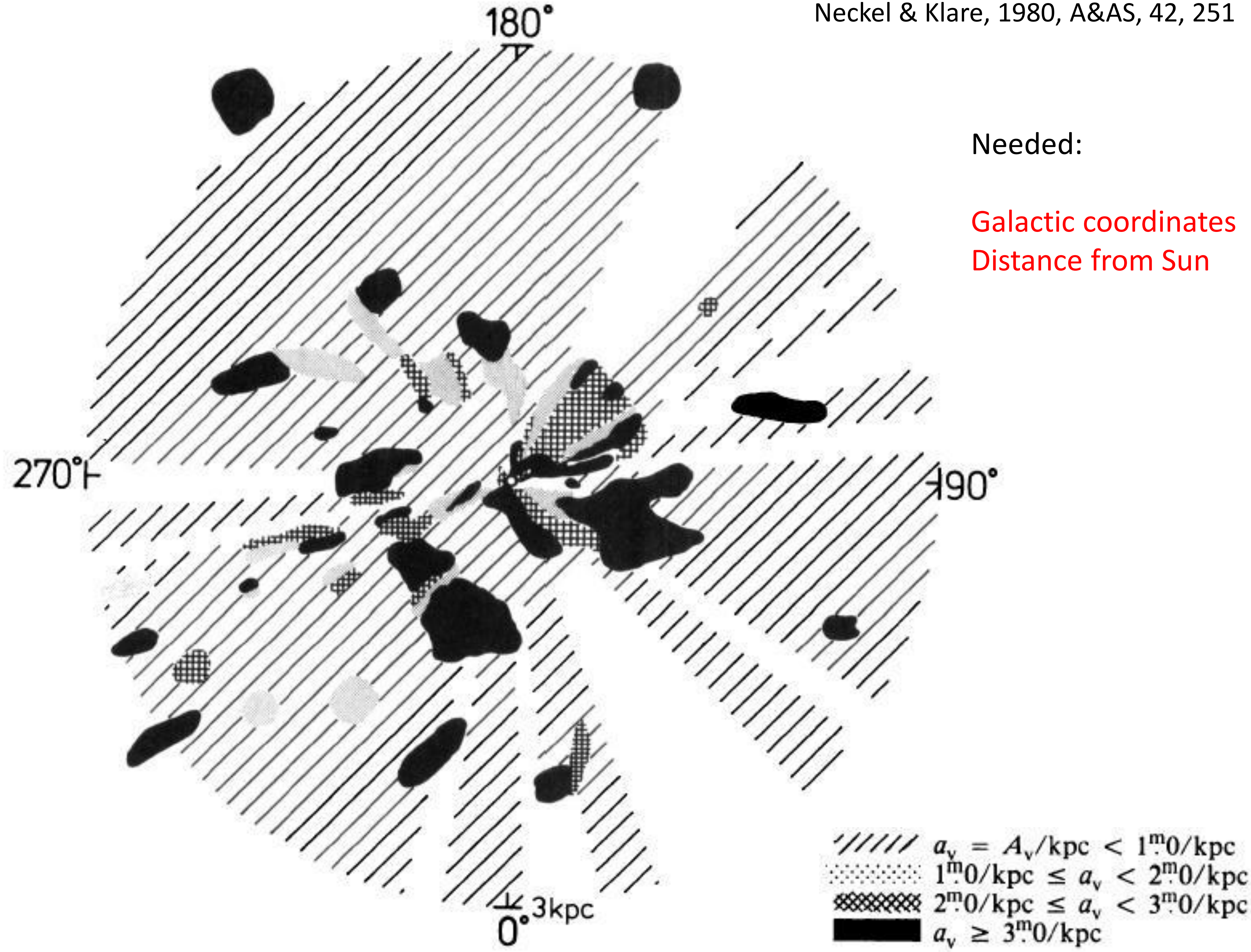
Piskunov et al., 2006, A&A, 445, 545

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

Needed:

Galactic coordinates

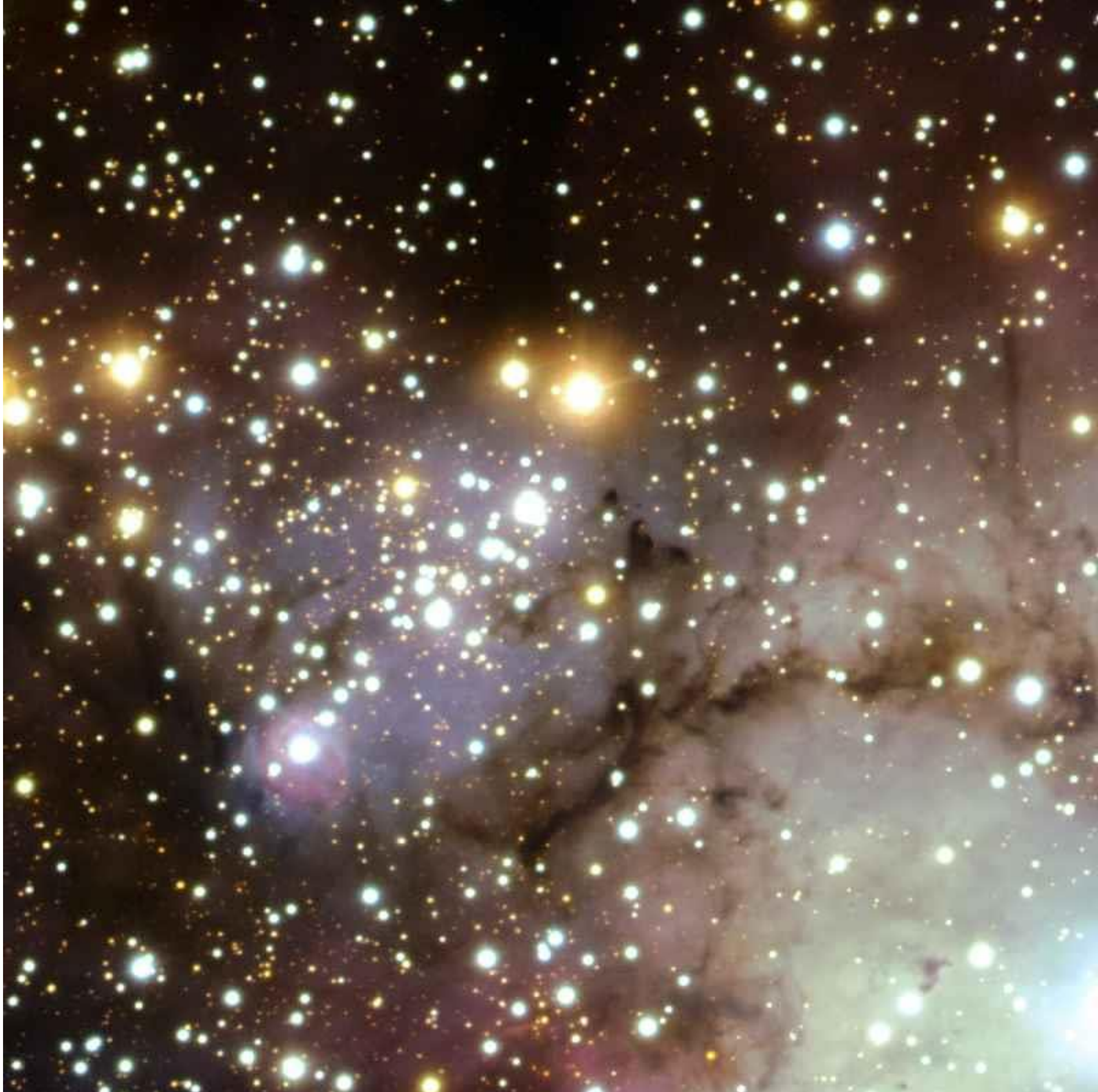
Distance from Sun



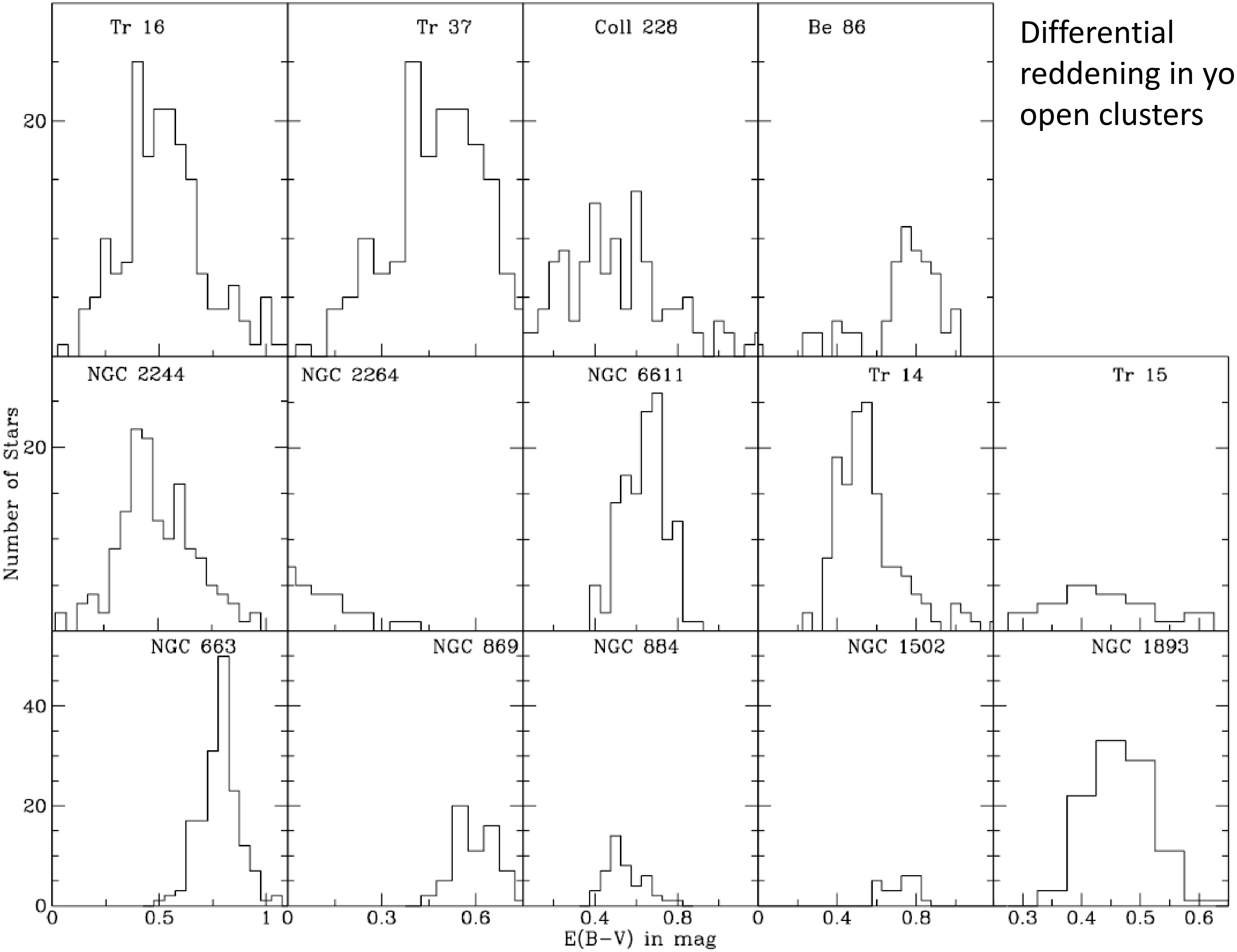
Haffner 18

Age about 8 Myr
d = 6000 pc

differential extinction within the cluster



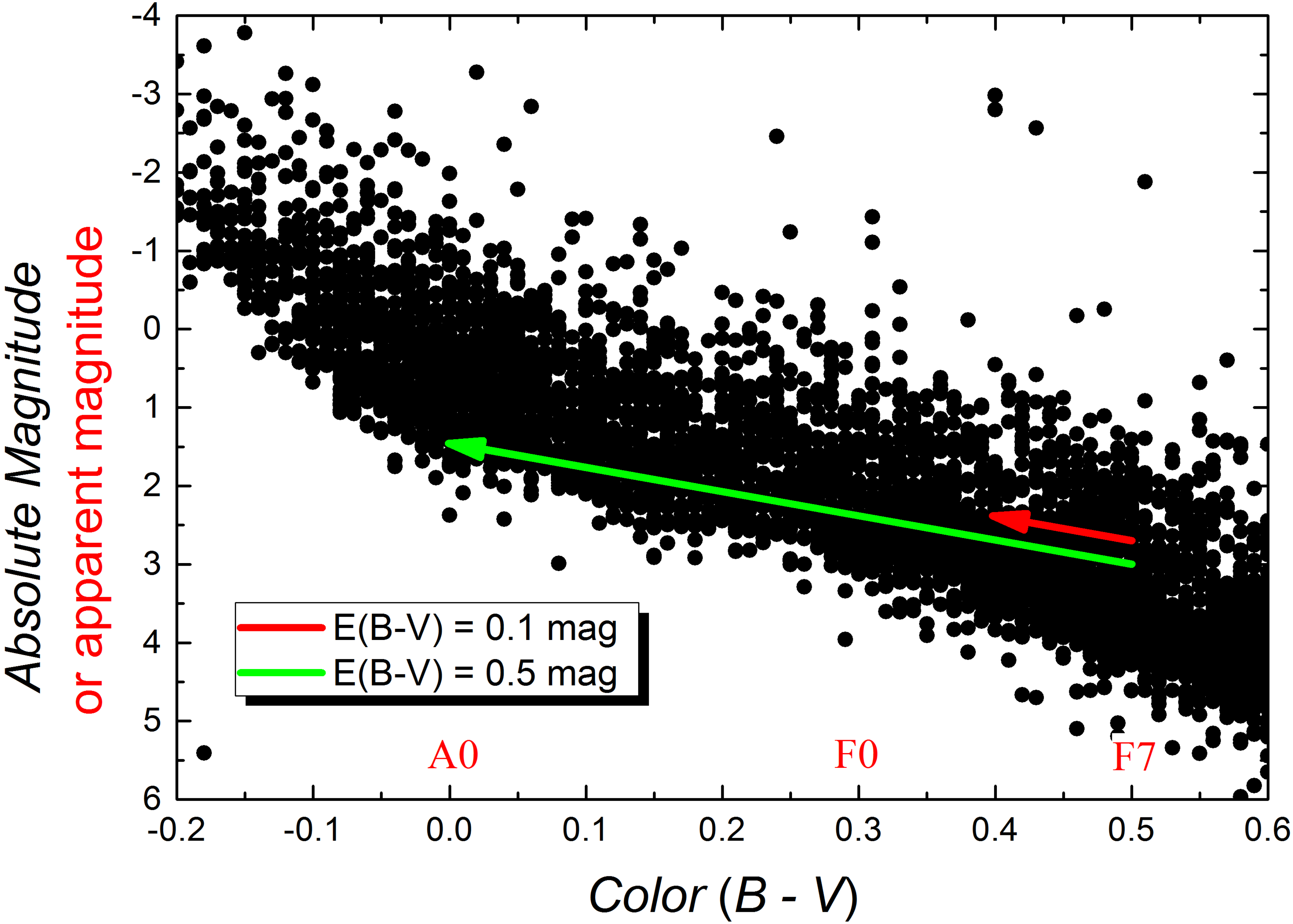
Differential reddening in young open clusters



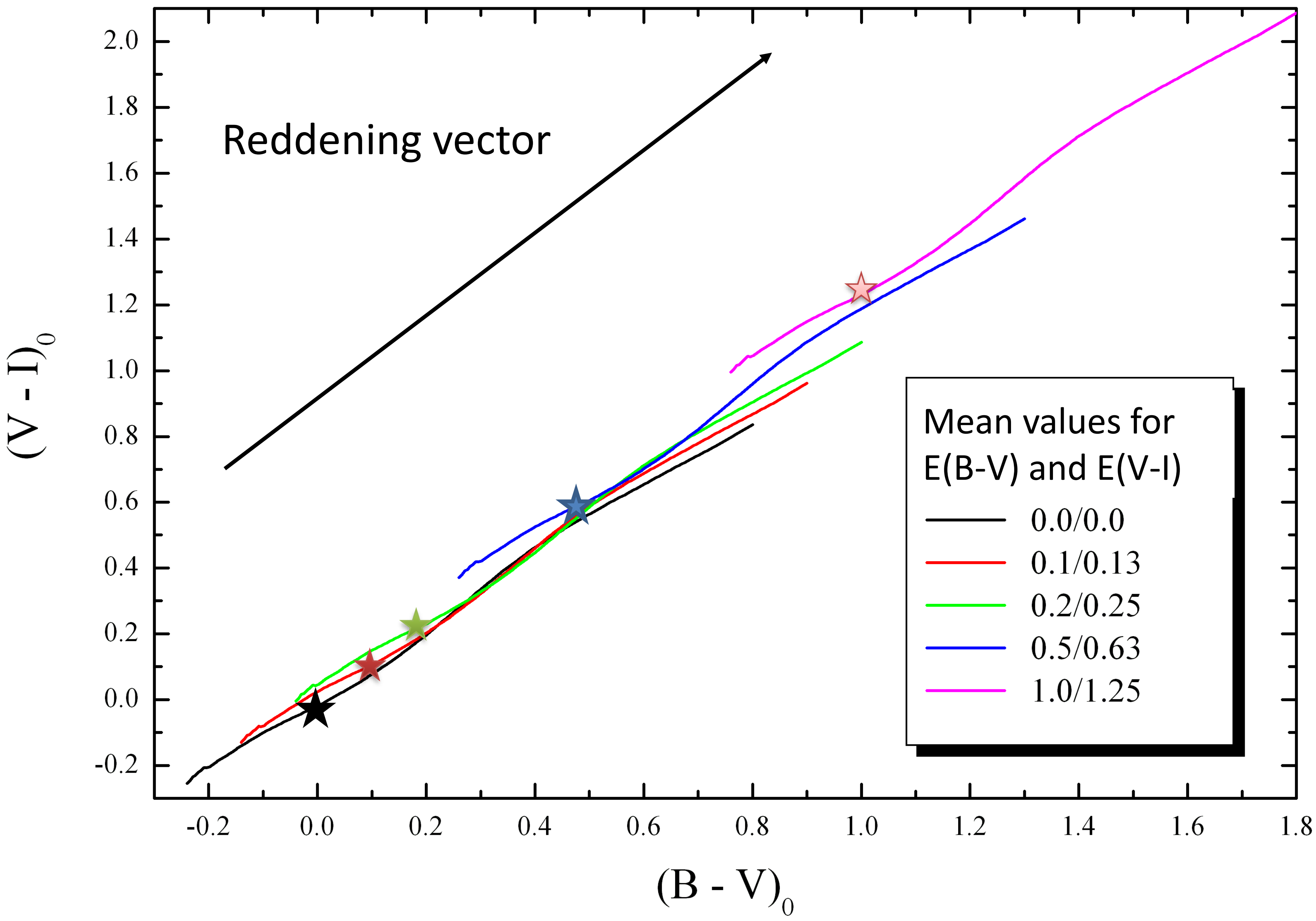
Yadav & Sagar, 2001, MNRAS, 328, 370

Determination of the reddening - Isochrones

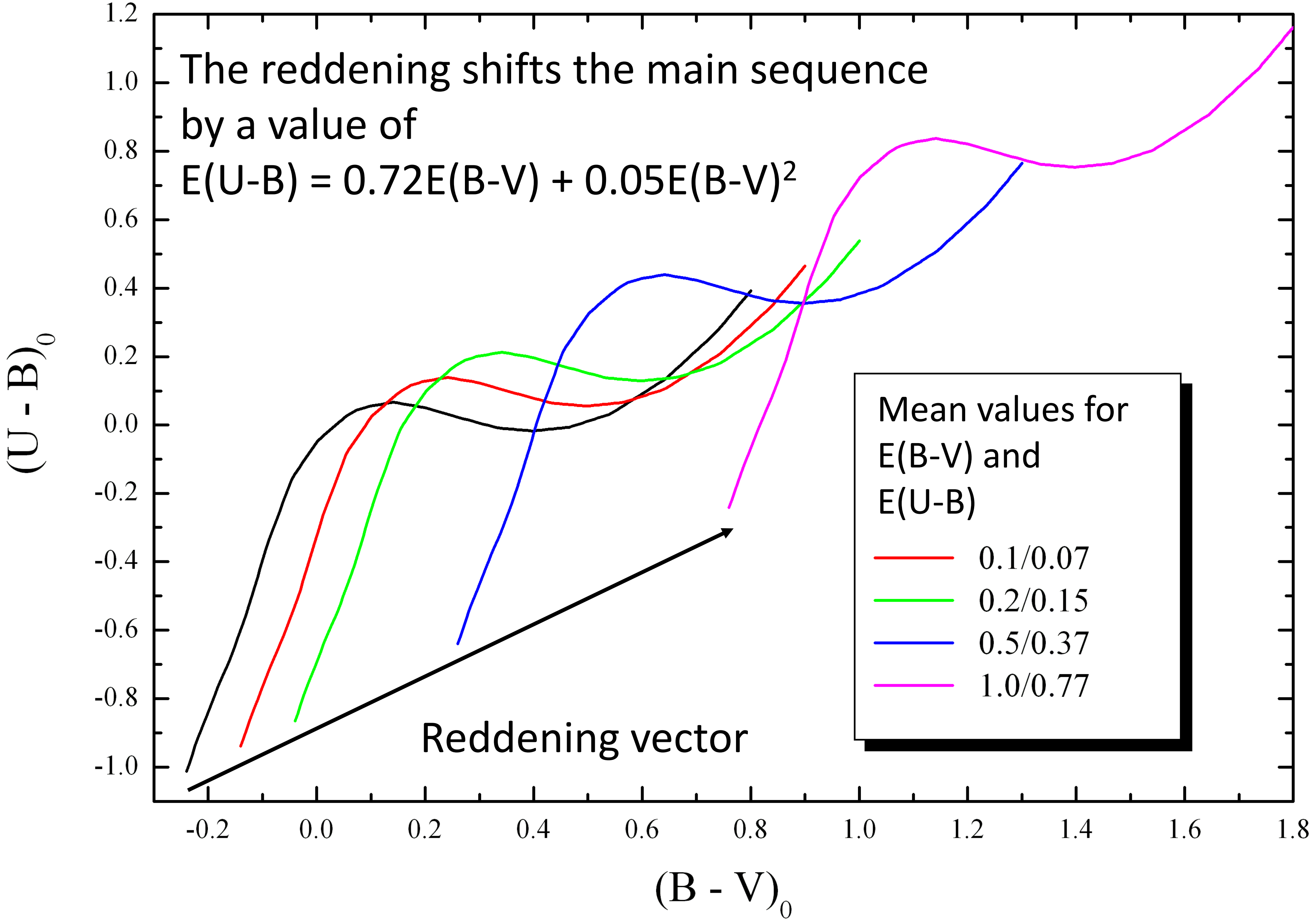
- From two temperature sensitive parameters, the determination of the reddening is not possible
- You need one “other” observational index
- First choices: (U – B), (u – b), [X], β
- Normally, you only have V, J, H, K, and so on



Absolute Magnitude
or apparent magnitude
Color (B - V)
-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
E(B-V) = 0.1 mag
E(B-V) = 0.5 mag
A0
F0
F7

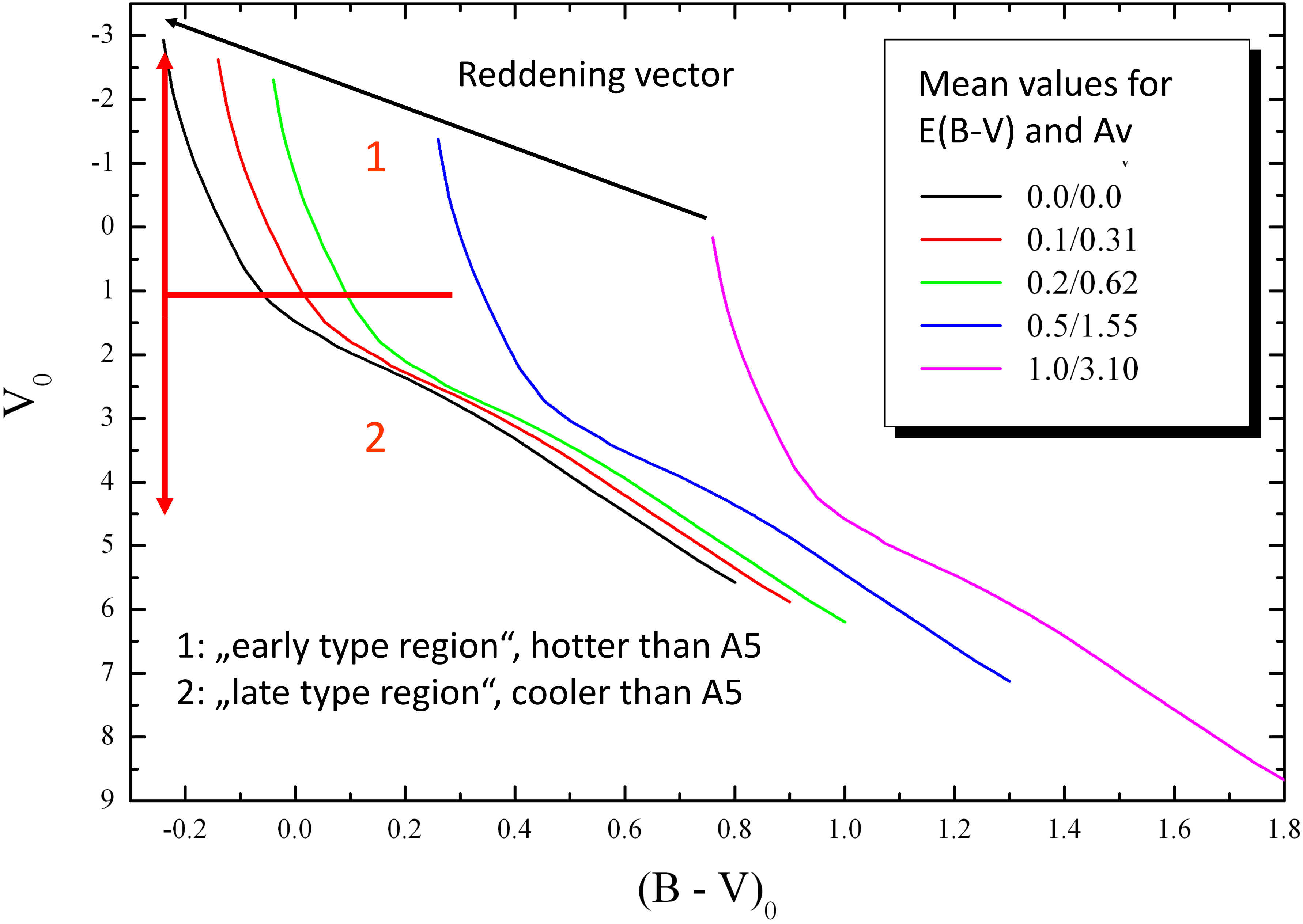


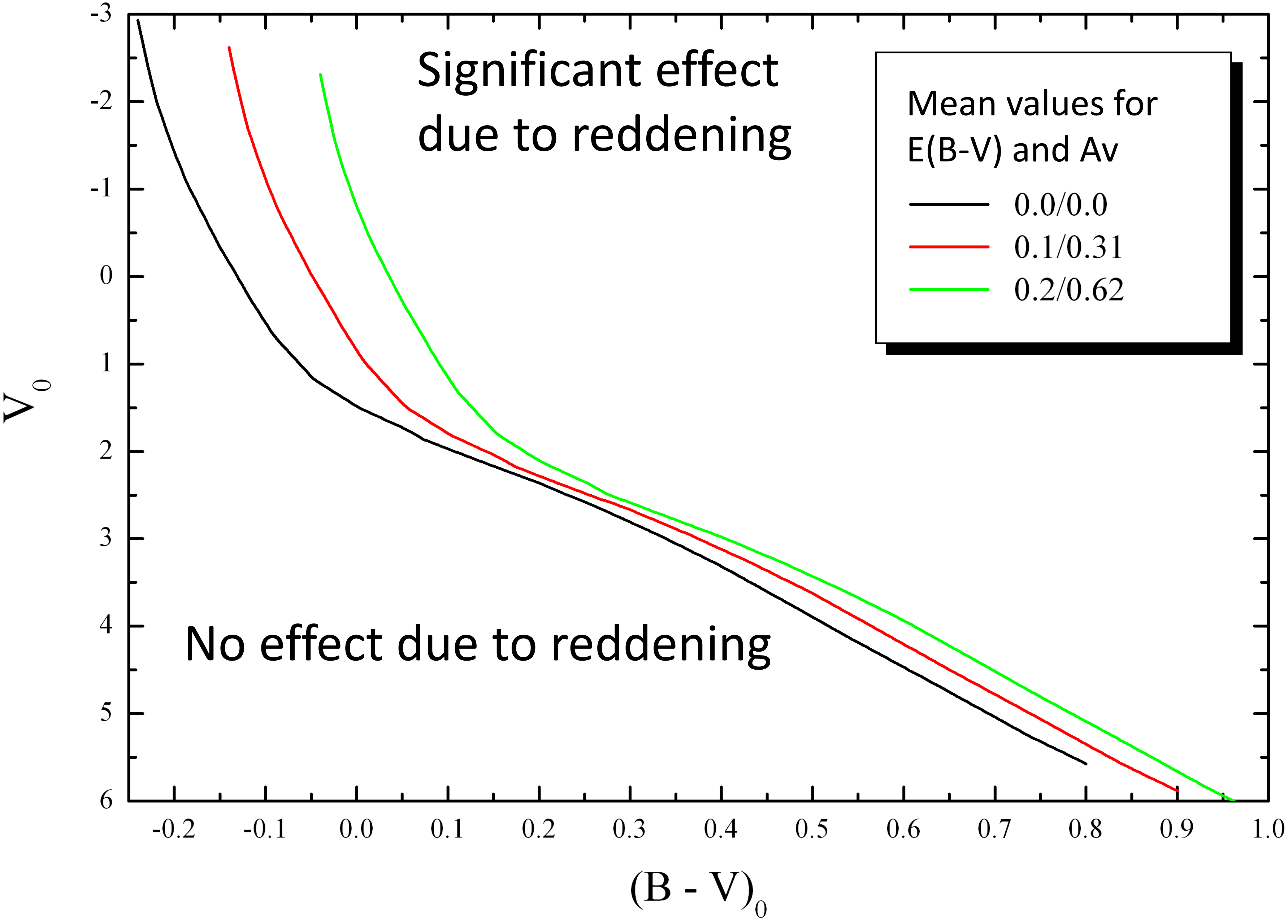
You would need a spectral information

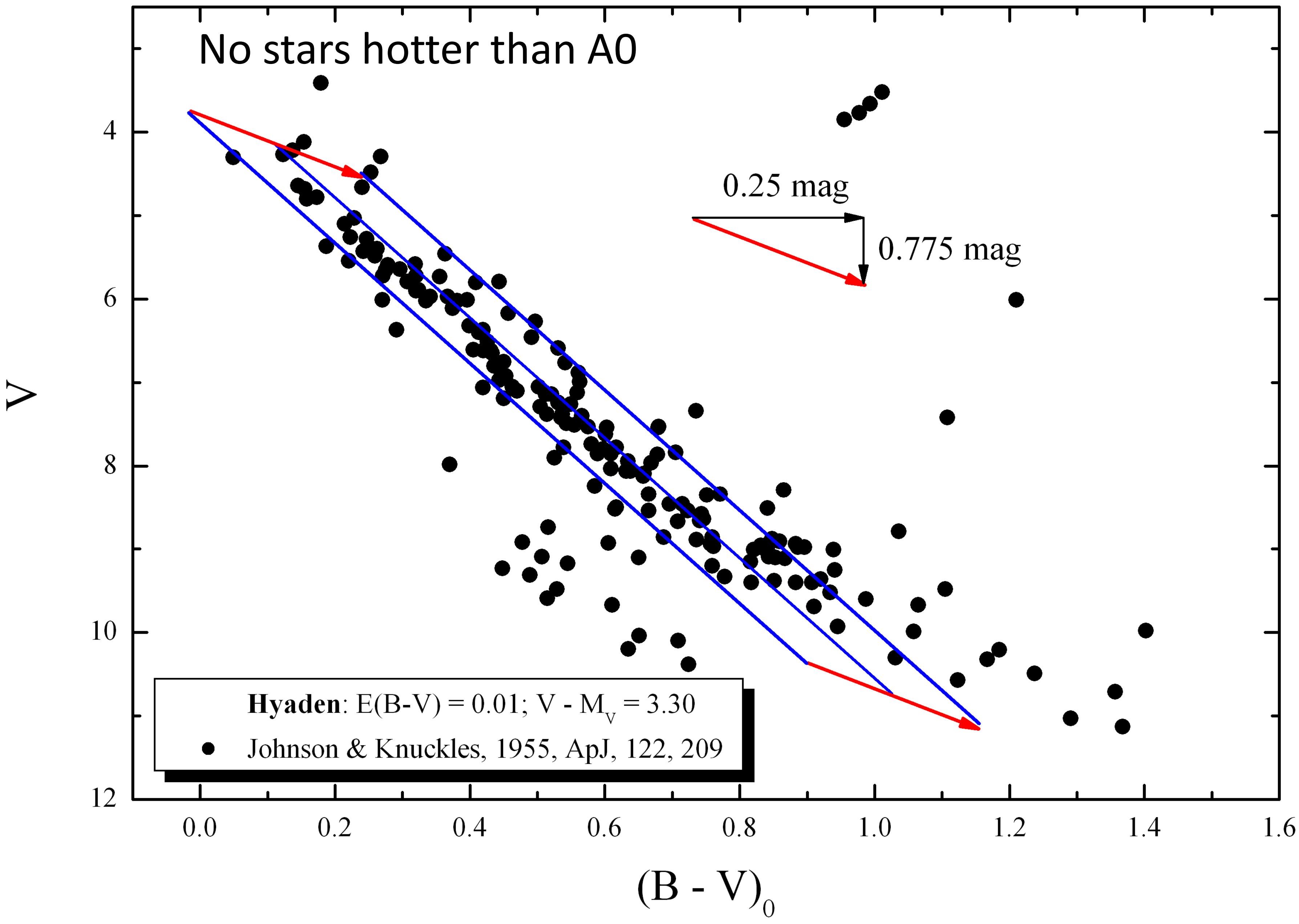


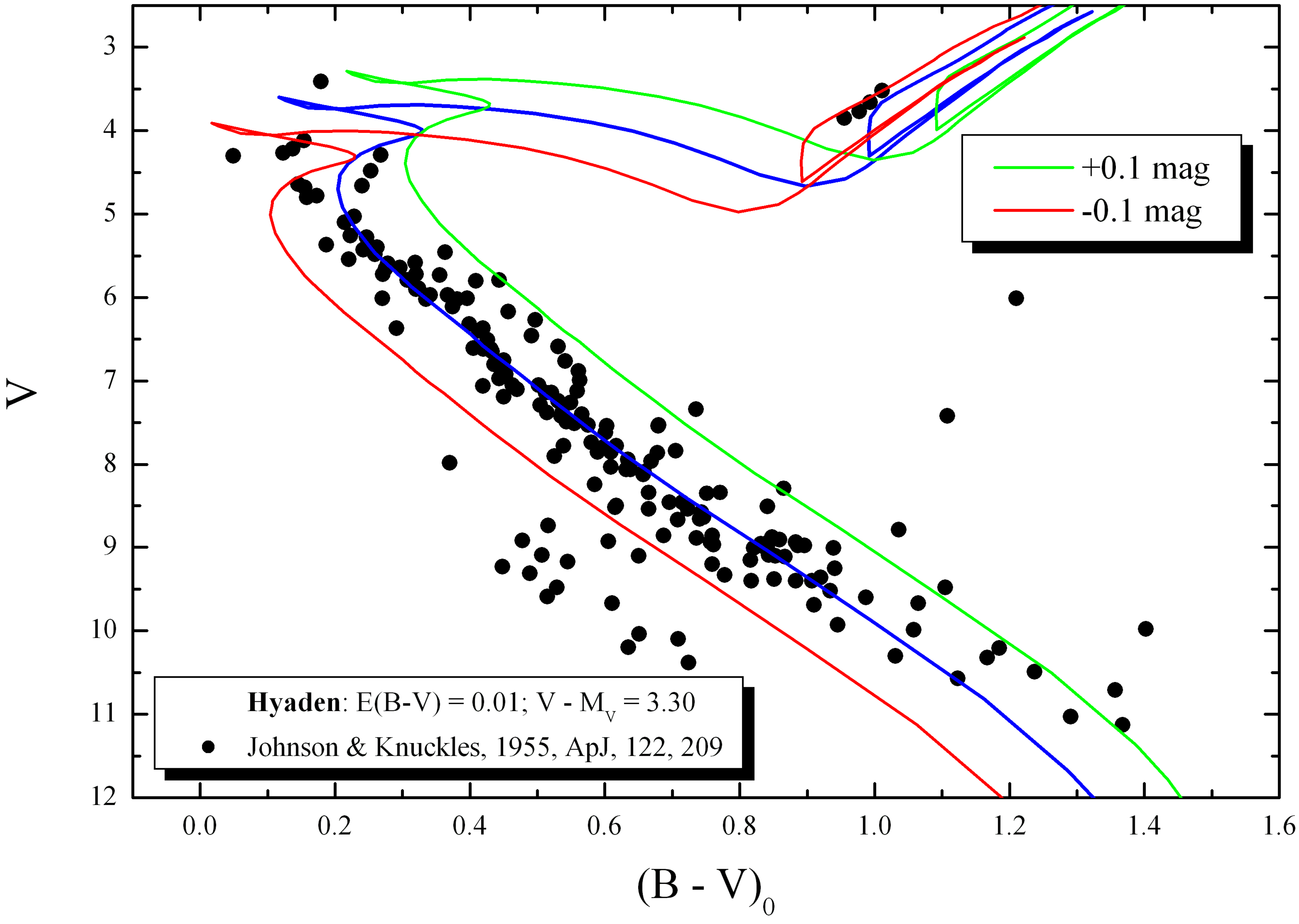
The reddening shifts the main sequence by a value of

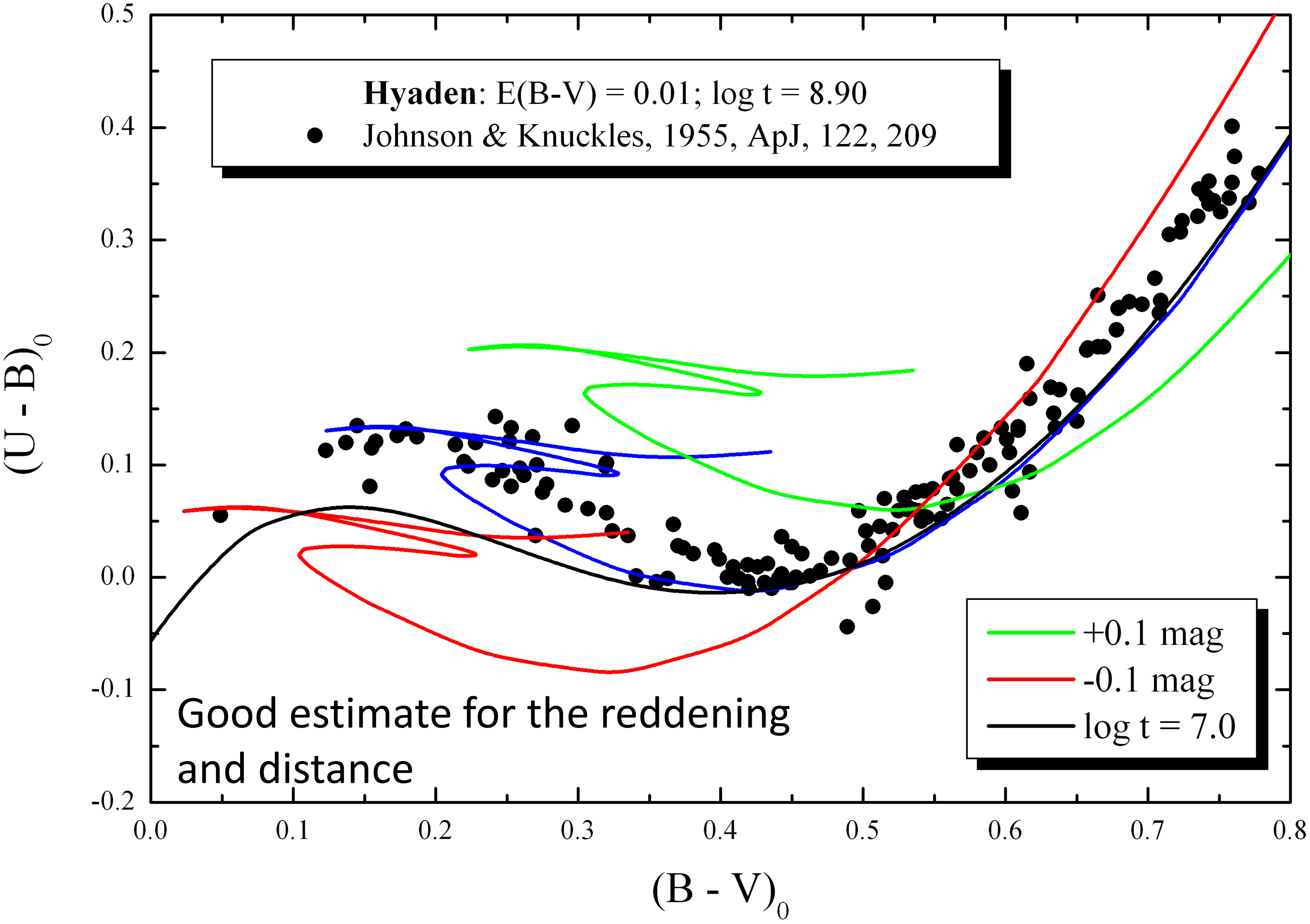
$E(U-B) = 0.72E(B-V) + 0.05E(B-V)^2$


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
V_0
$(B - V)_0$
-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
Hyaden: E(B-V) = 0.01; V - M_V = 3.30
● Johnson & Knuckles, 1955, ApJ, 122, 209
V
4
6
8
10
12
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
$(B - V)_0$


V
(B - V)$_0$
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
3
4
5
6
7
8
9
10
11
12
+0.1 mag
-0.1 mag
Hyaden: E(B-V) = 0.01; V - M$_V$ = 3.30
● Johnson & Knuckles, 1955, ApJ, 122, 209



Good estimate for the reddening and distance

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

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

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

$$\boxed{V - M_v} - A_v = 5 \lg r - 5 . \qquad (3)$$

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

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

$$- (V - M_v(\beta) - A_v(UBV, \beta)) . \qquad (4)$$

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!

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

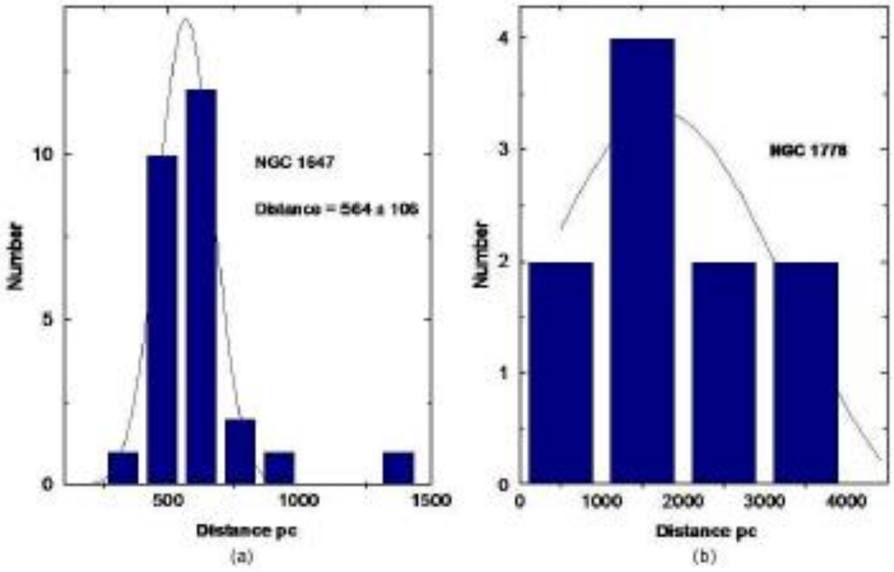


Fig. 3. Histogram of the distances for the stars in the direction of (a) NGC 1647 and (b) NGC 1778. The thin line is a Gaussian fit to the data.

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

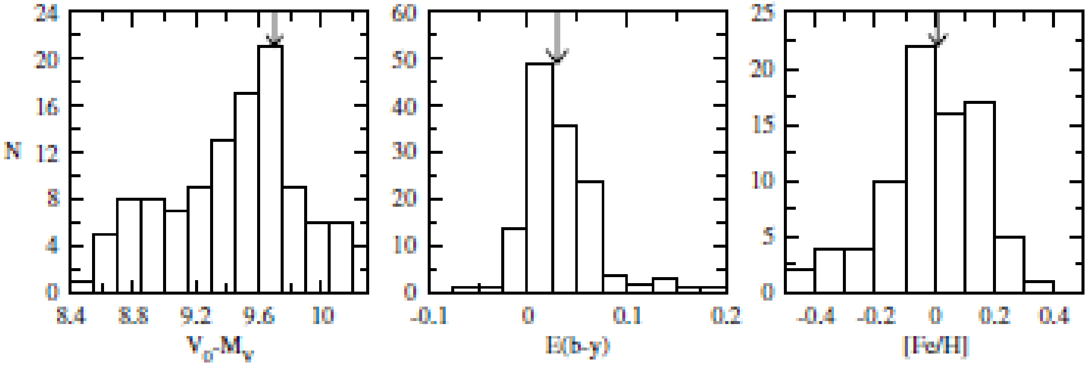
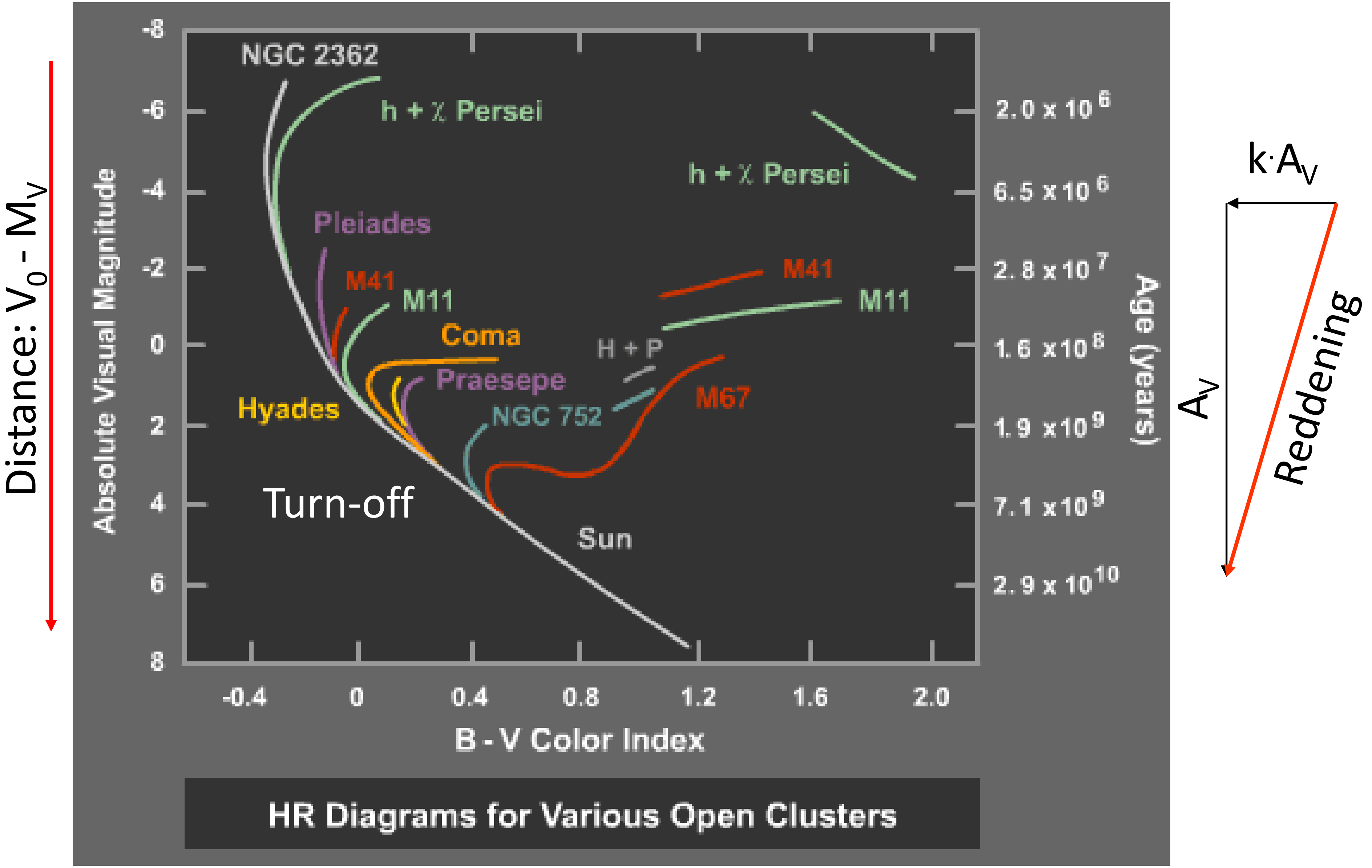


Fig. 9. The histograms of the distance modulus, reddening and metallicity of the selected member stars of M 67 with H_β measurements. The arrows indicate the mean values adopted for the cluster.

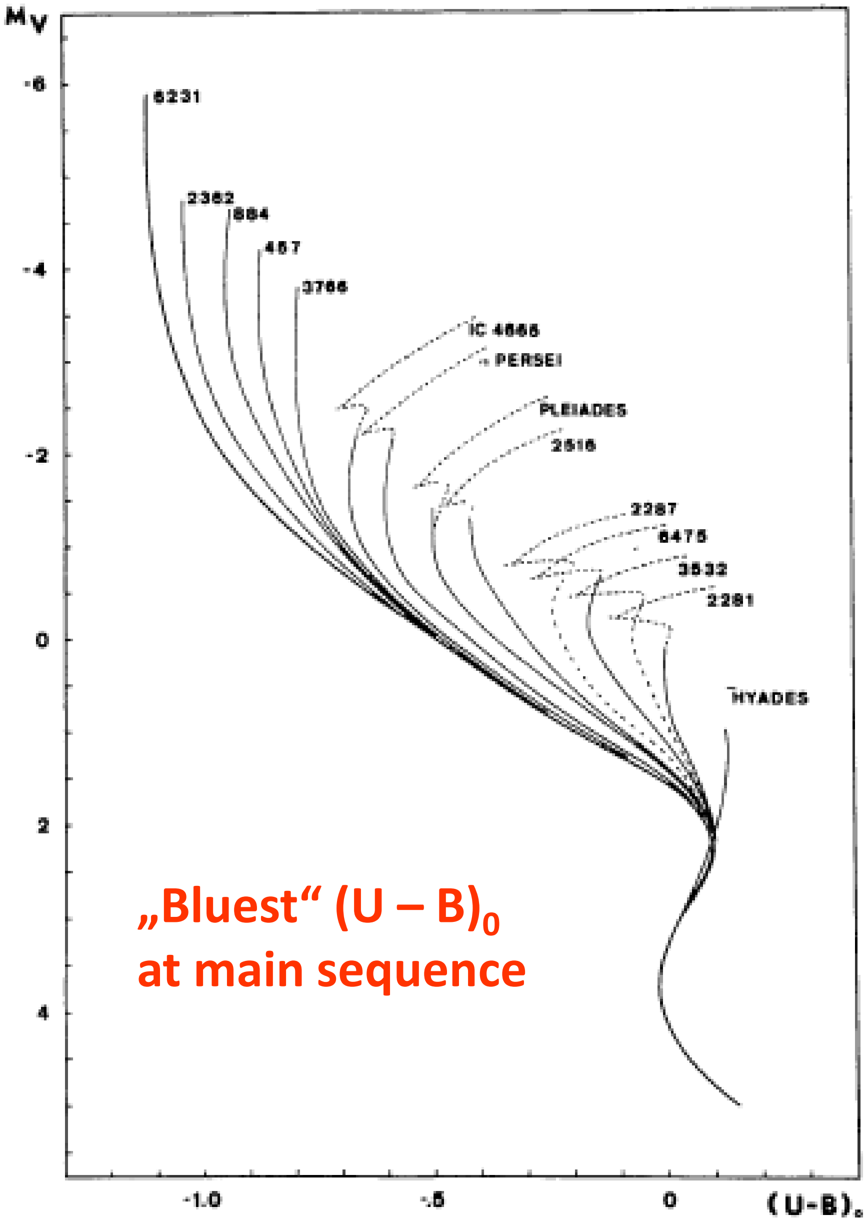


HR Diagrams for Various Open Clusters

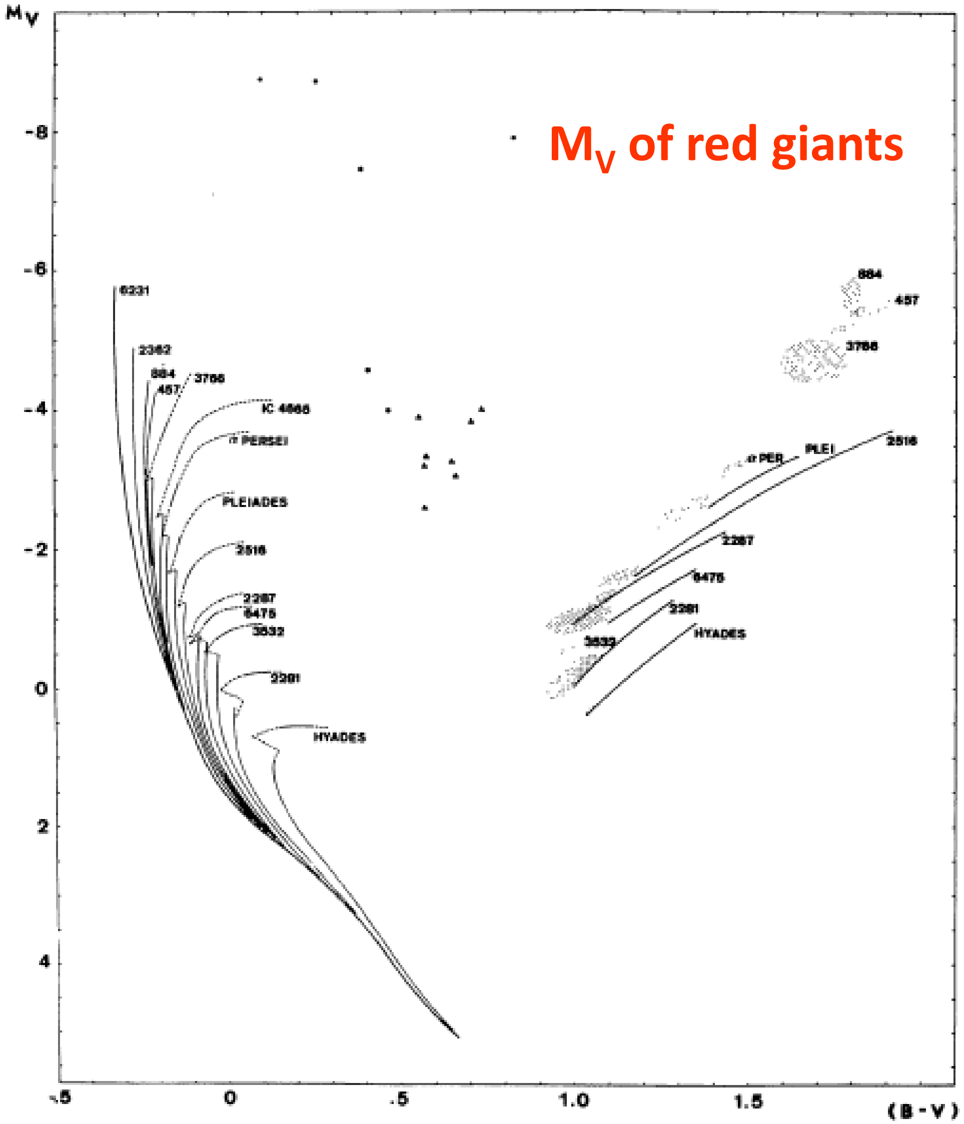
Turn off point

- Where is the turn-off point located?
  - Color/temperature
  - Absolute/apparent magnitude/luminosity
- Direct correlation with the age
- Difficult to define for young star clusters
- First, classical method, just „to look“ at color-magnitude-diagram

Mermilliod, 1981, A&A, 97, 235: no newer paper available!



„Bluest“ $(U - B)_0$ at main sequence



M_V of red giants

Dereddened indices

Mermilliod, 1981, A&A, 97, 235

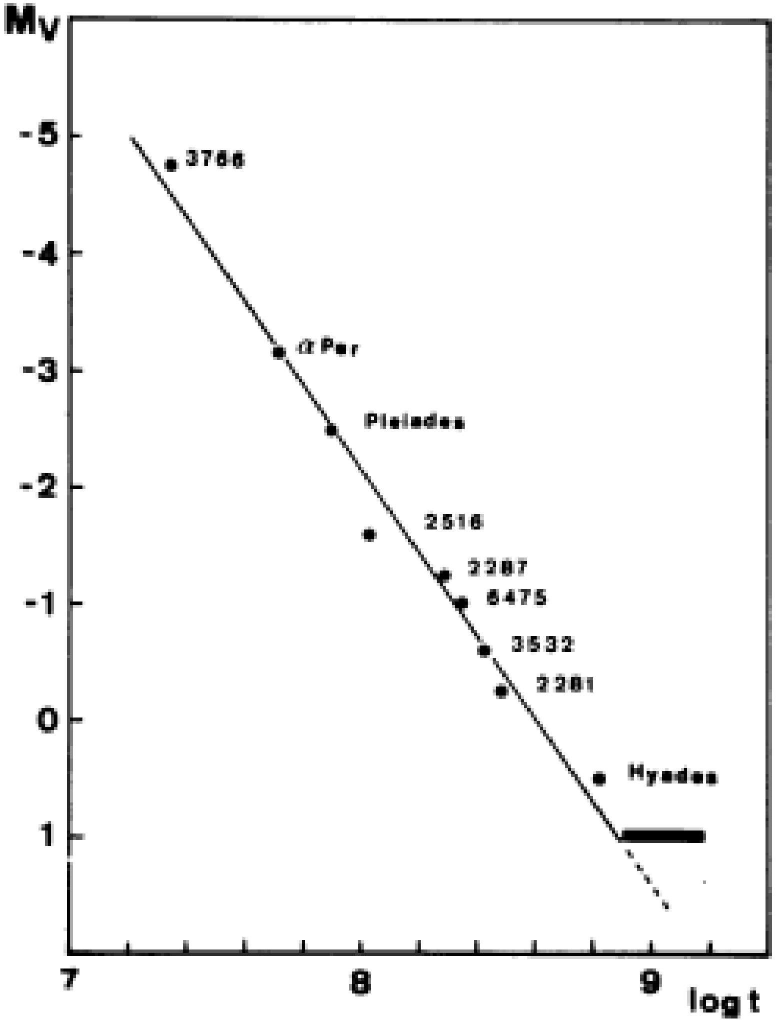


Fig. 7. Relation between the mean absolute magnitude of the red giant concentrations and log *t*. The darkened area at M_V=+1. indicates the position of the clump in old clusters.

A correlation has been established between the mean absolute magnitude of the red giant concentrations and ages (Fig. 7). A straight line has been fitted by eye, which gives the following relation:

$$\log t = 0.280\, M_V + 8.610$$

No direct error estimation possible

Possible to use for star clusters between 20 Myr and 800 Myr

Mermilliod, 1981, A&A, 97, 235

Very precise method

Possible to use between for star clusters between 20 Myr and 300 Myr

$(U - B)_0$ for cooler stars
= older ages
is almost **constant**

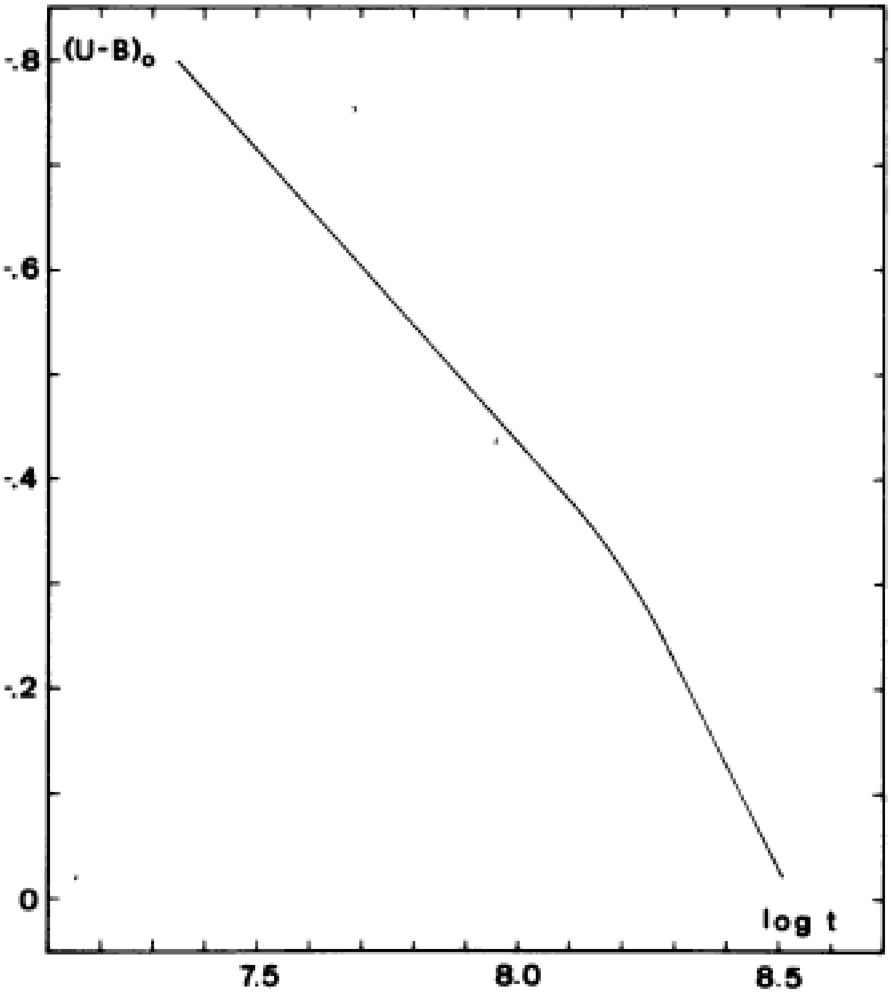
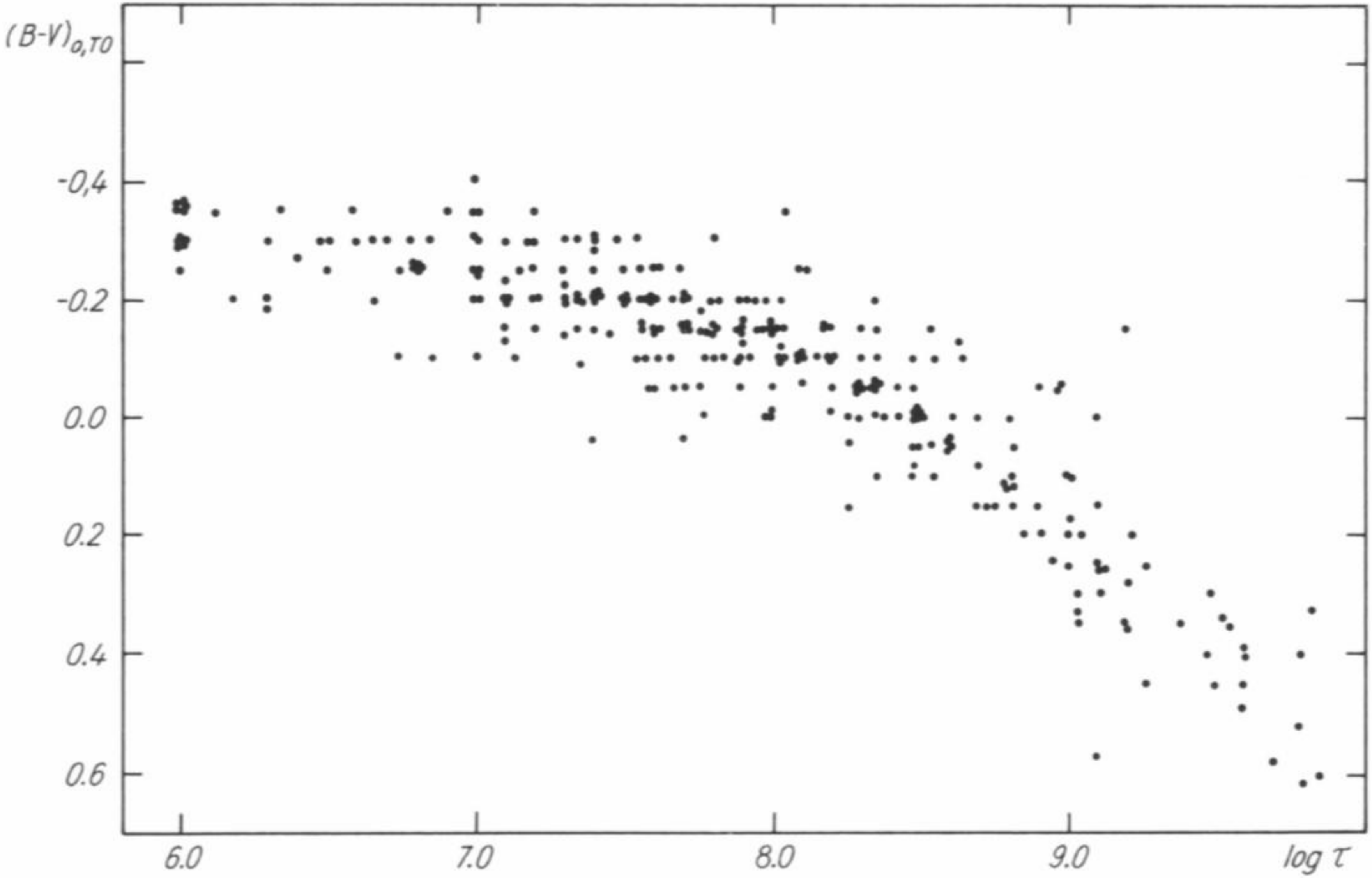


Fig. 6. Calibration of the bluest $(U-B)_o$ on the main sequence in terms of age (log t)

$$-.80 \leq (U-B)_o < -.35 \quad \log t = 1.795(U-B)_o + 8.785$$
$$-.28 \leq (U-B)_o < .00 \quad \log t = 0.813(U-B)_o + 8.487$$



Not very accurate but still useful, never done for 2MASS and NIR

Calculation of Isochrones

The calculation of theoretical isochrone (= lines of equal age) is done with stellar atmospheres

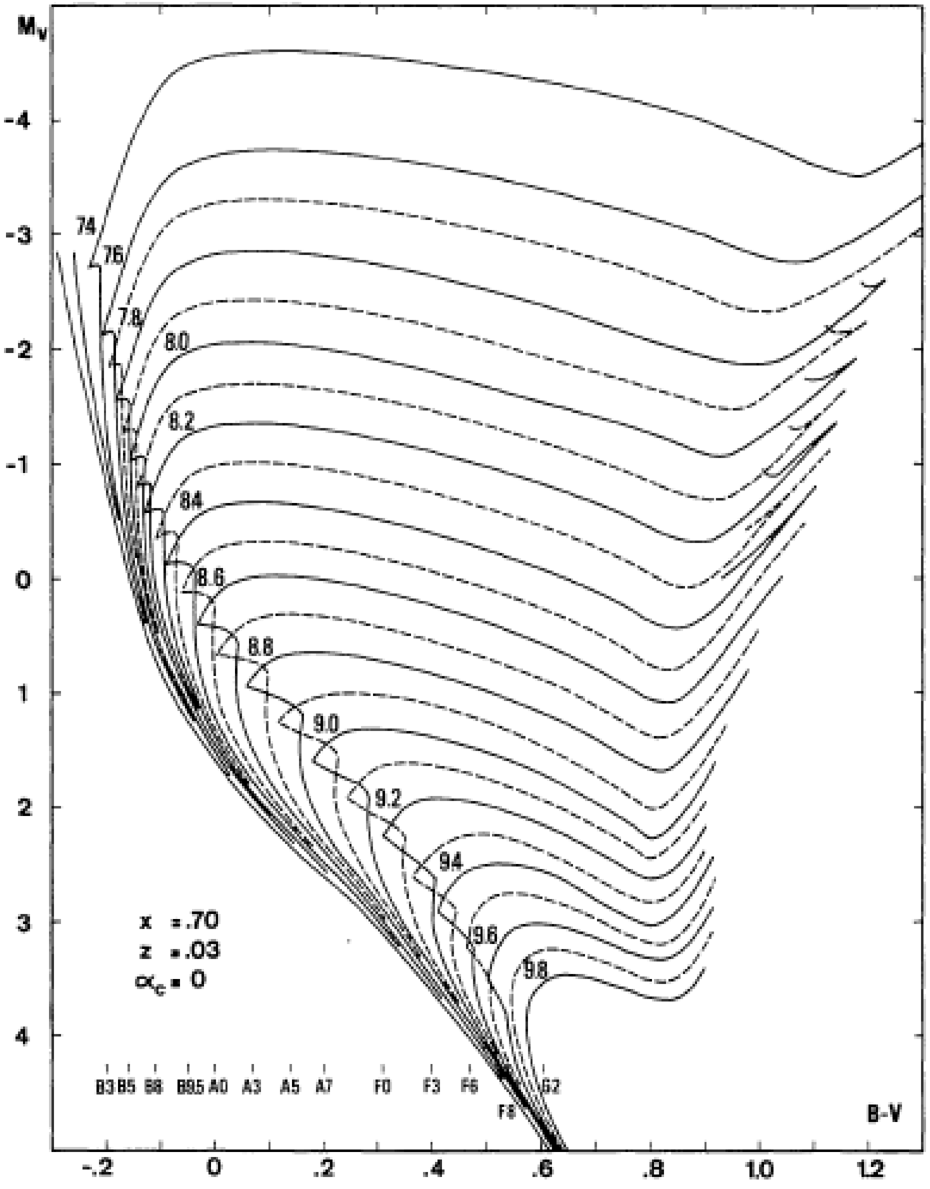
Free parameter : Metallicity [X, Y, Z]

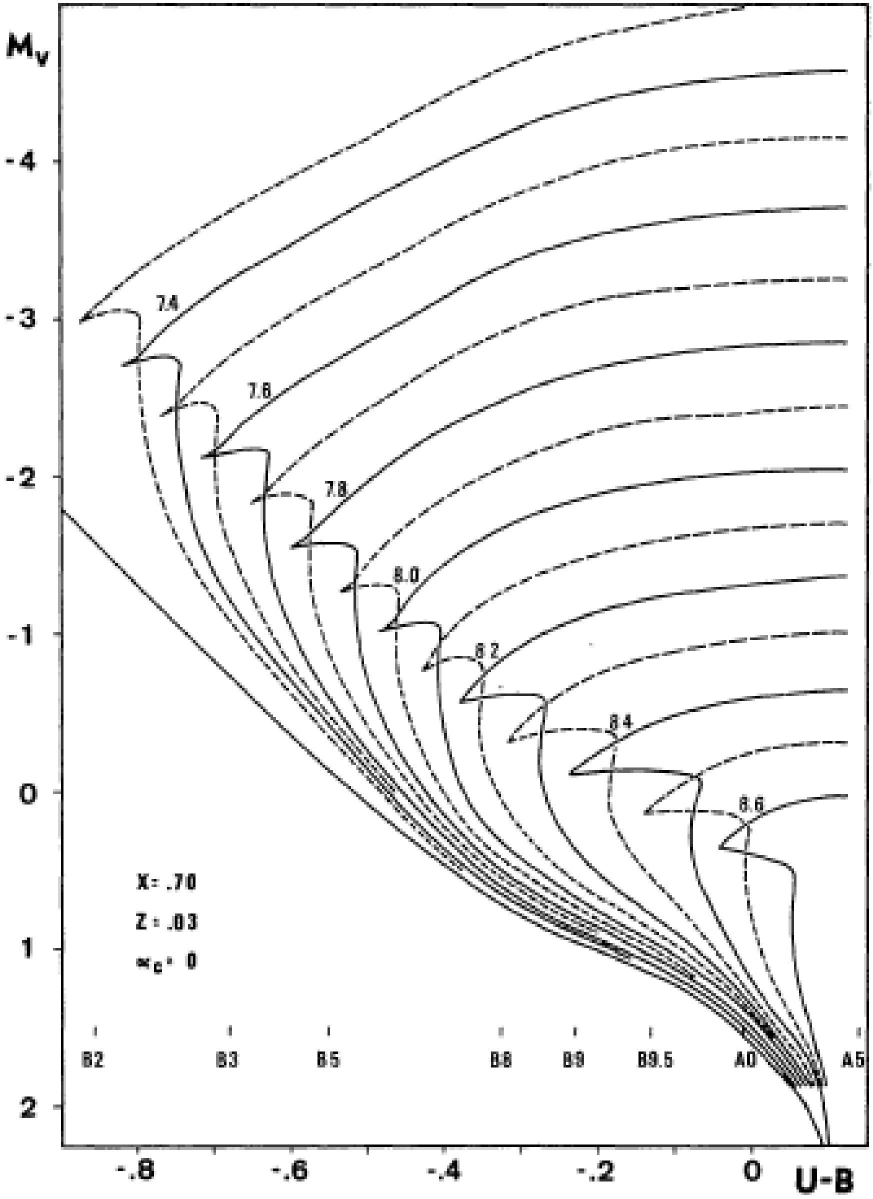
1. Zero Age Main Sequence $[T_{\mathrm{eff}}, L]_0$
2. Chemical and gravitational evolution
3. $[T_{\mathrm{eff}}, L](\mathrm{t})$
4. Adequate stellar atmosphere = **PHYSICS**
5. Absolute fluxes
6. Folding with filter curves
7. Colors, absolute magnitudes and so on

Which astrophysical “parameters” are important?

- Equations of state
- Opacities
- Model of convection
- Rotation
- Mass loss
- Magnetic field
- Core Overshooting
- Abundance of helium
- …

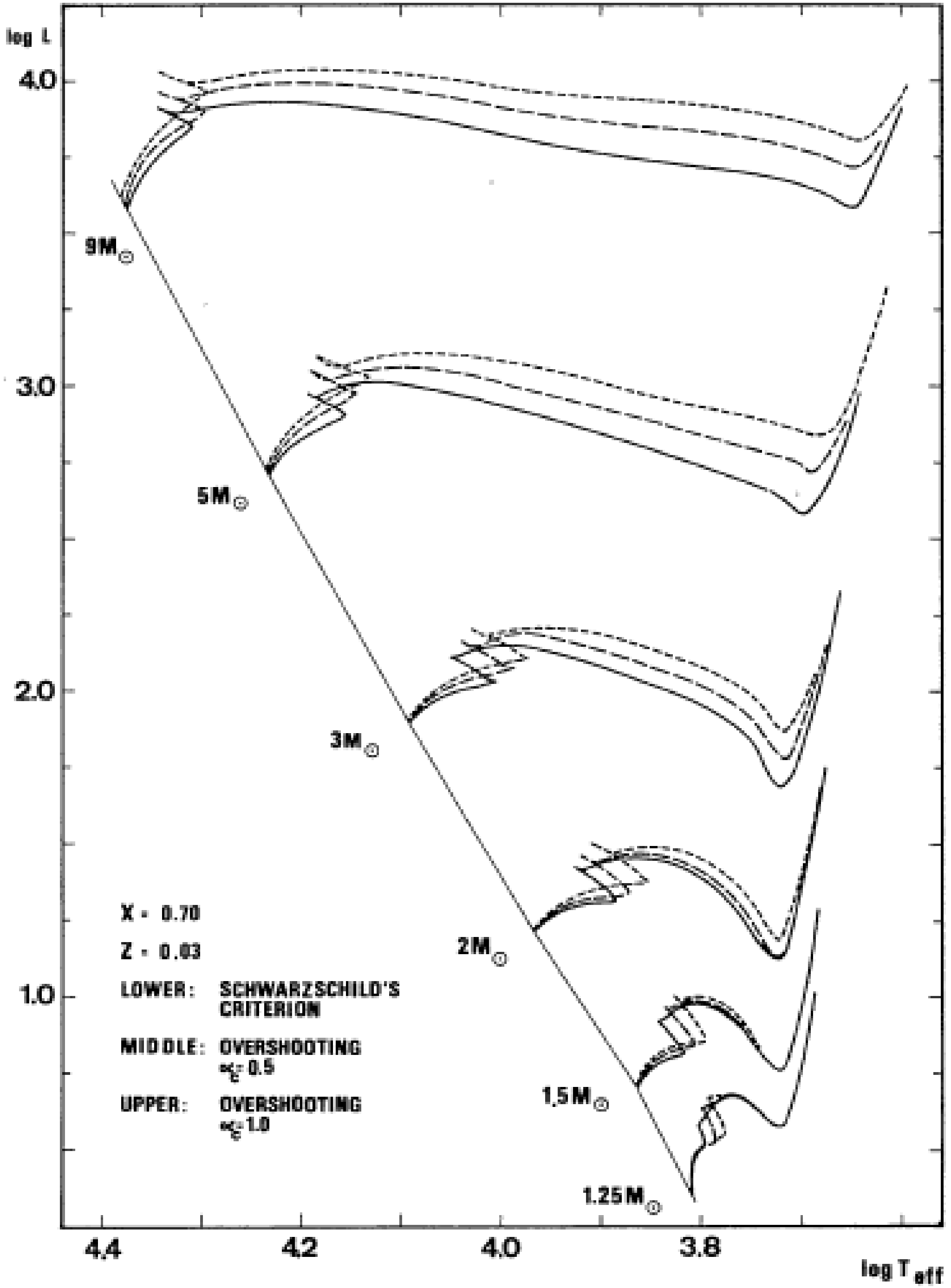
Maeder & Mermilliod, 1981, A&A, 93, 136





Maeder & Mermilliod, 1981, A&A, 93, 136

Different treatment of convection

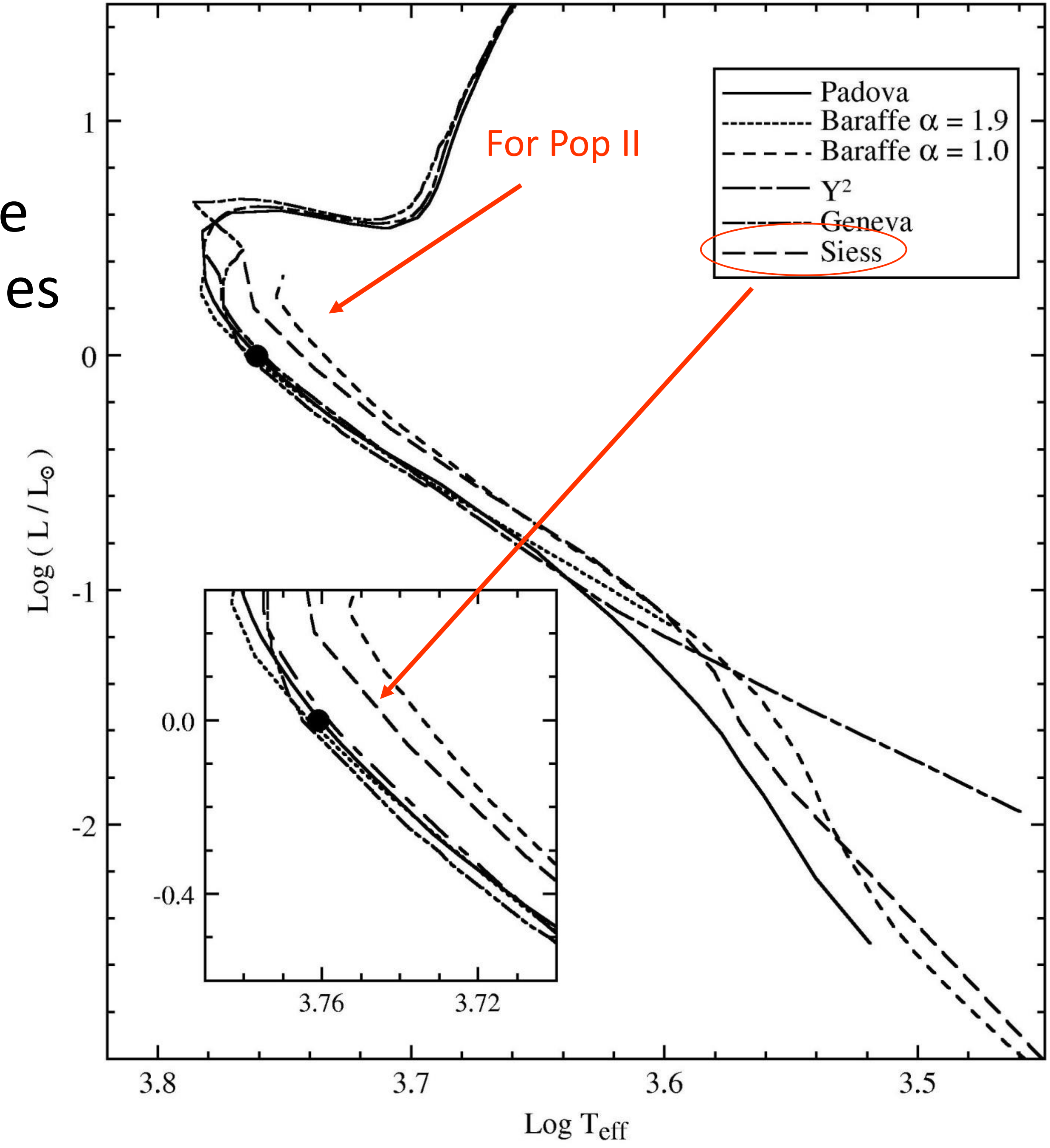


A comparison of isochrone sets

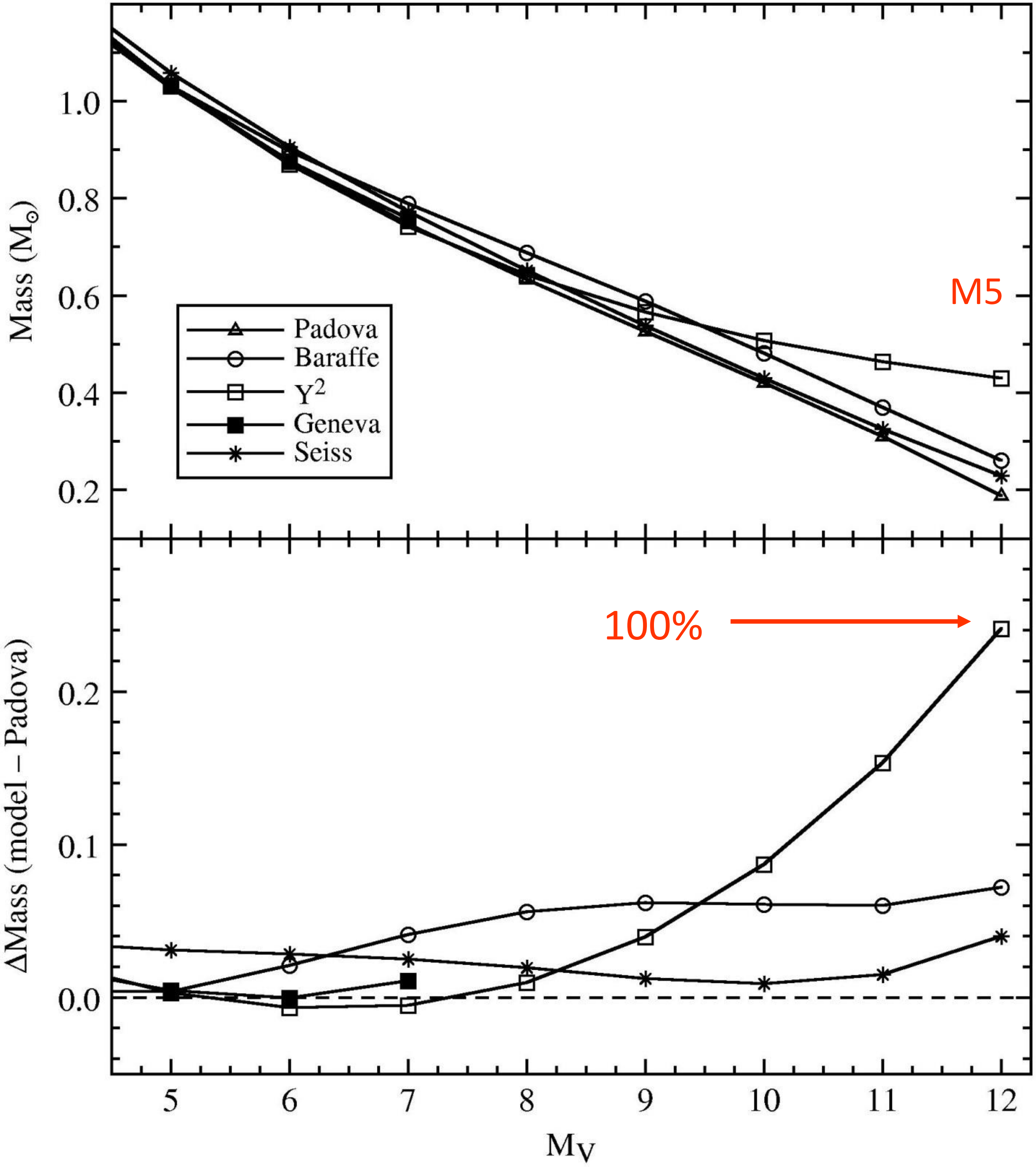
- Grocholski & Sarajedini (2003, MNRAS, 345, 1015) compared the following isochrones:
  1. “Padova”: Girardi et al., 2002, A&A, 391, 195
  2. Baraffe: Baraffe et al., 1998, A&A, 337, 403
  3. “Geneva”: Lejeune & Schaerer, 2001, A&A, 366, 538
  4. Y^2: Yi et al., 2001, ApJS, 136, 417
  5. Siess: Siess et al., 2000, A&A, 358, 593

The location of the Sun with isochrones of 5 Gyr

Isochrones by Siess et al. (1997) seem “to have a problem”


For Pop II

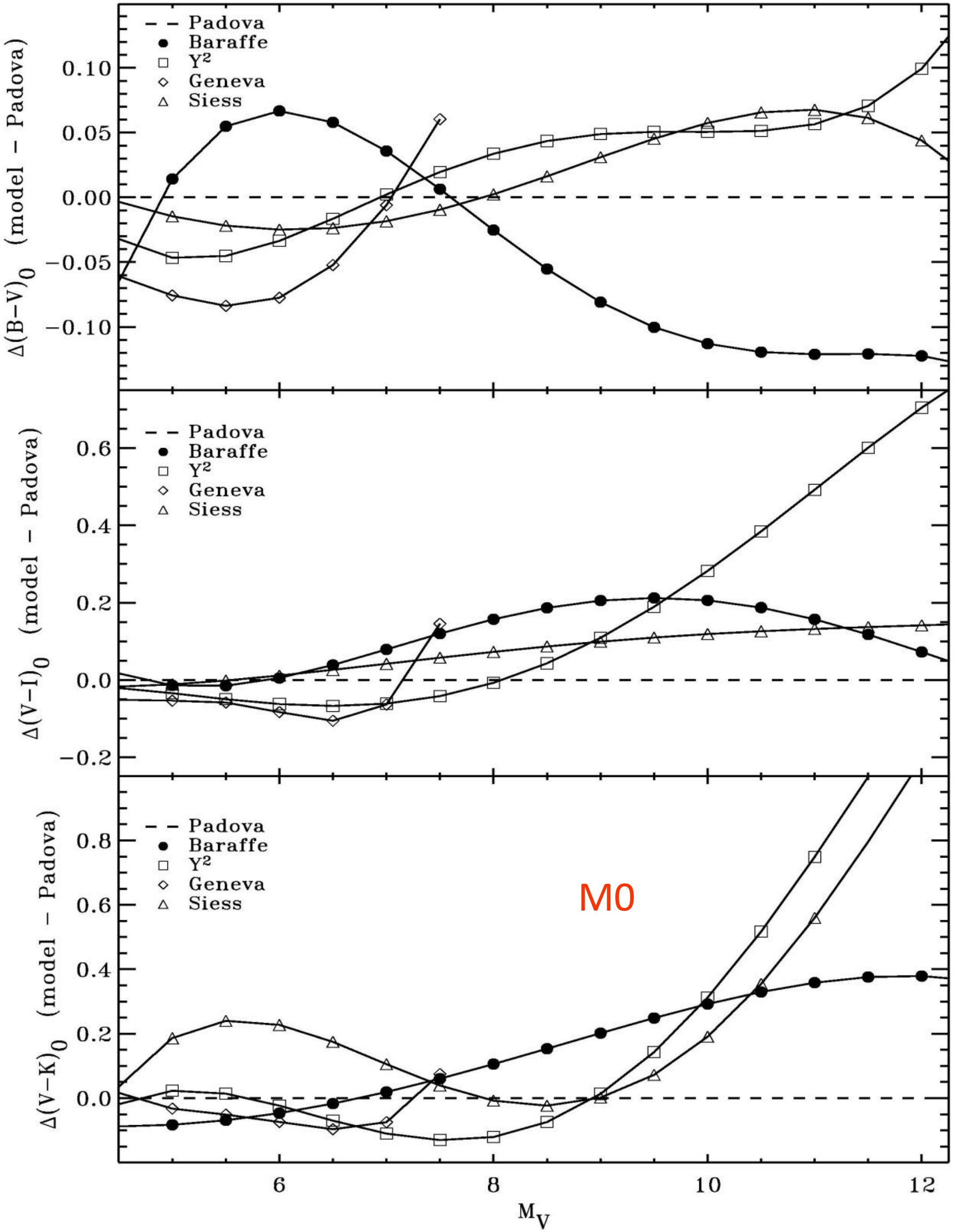
Comparison of different masses for a constant M_V

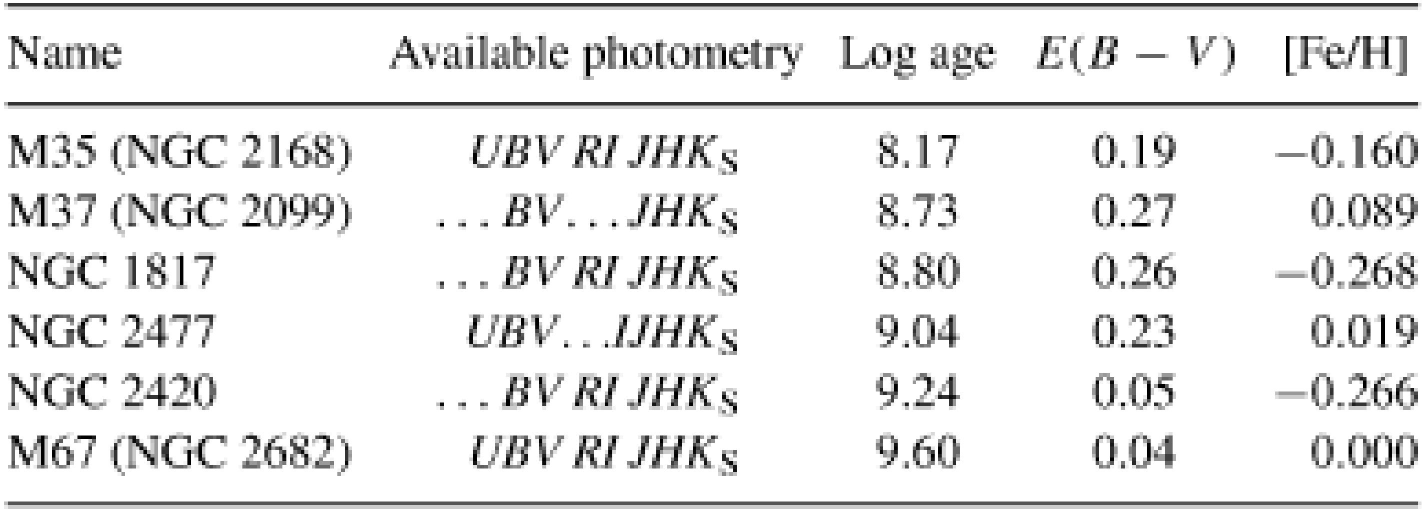


Zero line is the isochrone of the Padova group

Comparison of different color indices for a constant M_V

Zero line is the isochrone of the Padova group

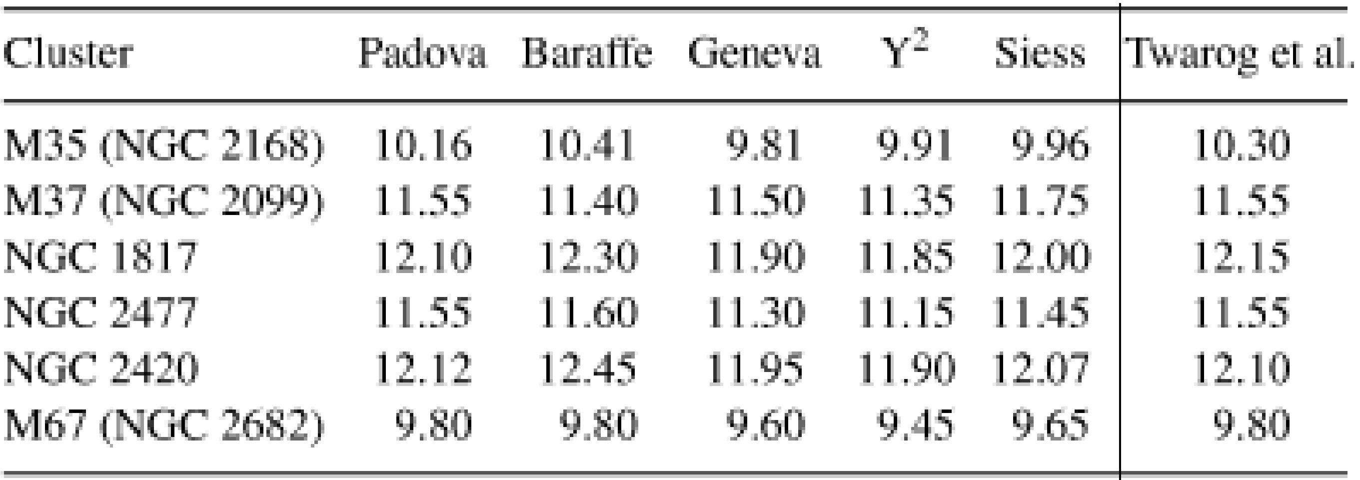




Name	Available photometry	Log age	$E(B-V)$	[Fe/H]
M35 (NGC 2168)	$UBV\ RI\ JHK_\mathrm{S}$	8.17	0.19	−0.160
M37 (NGC 2099)	$\dots BV \dots JHK_\mathrm{S}$	8.73	0.27	0.089
NGC 1817	$\dots BV\ RI\ JHK_\mathrm{S}$	8.80	0.26	−0.268
NGC 2477	$UBV \dots IJHK_\mathrm{S}$	9.04	0.23	0.019
NGC 2420	$\dots BV\ RI\ JHK_\mathrm{S}$	9.24	0.05	−0.266
M67 (NGC 2682)	$UBV\ RI\ JHK_\mathrm{S}$	9.60	0.04	0.000

Used
Photometry

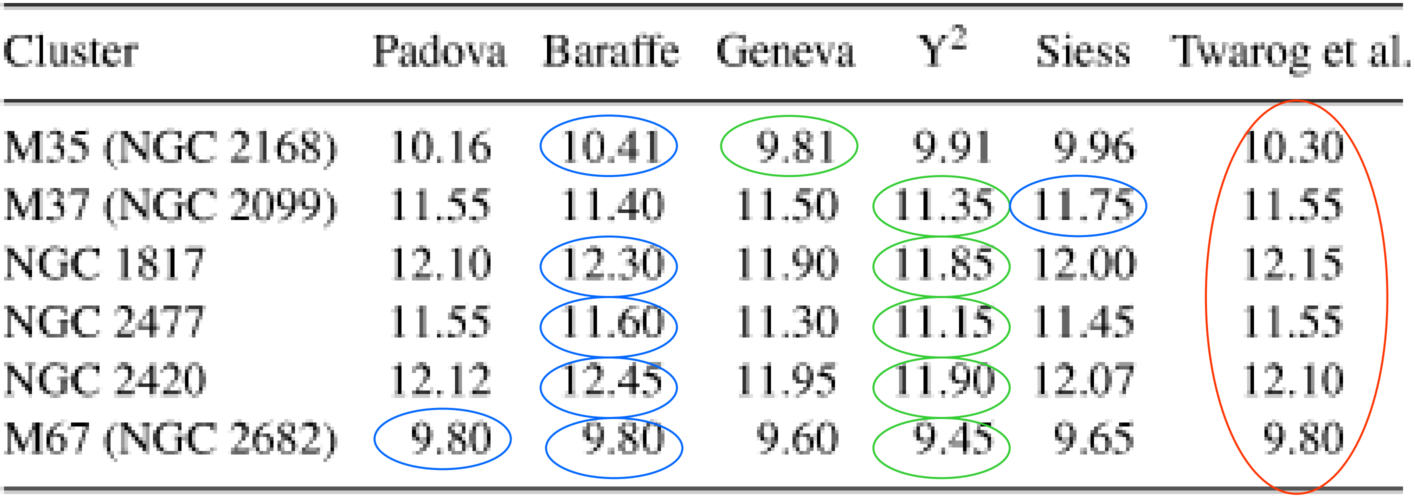
Parameters from the literature



Cluster	Padova	Baraffe	Geneva	Y^2	Siess	Twarog et al.
M35 (NGC 2168)	10.16	10.41	9.81	9.91	9.96	10.30
M37 (NGC 2099)	11.55	11.40	11.50	11.35	11.75	11.55
NGC 1817	12.10	12.30	11.90	11.85	12.00	12.15
NGC 2477	11.55	11.60	11.30	11.15	11.45	11.55
NGC 2420	12.12	12.45	11.95	11.90	12.07	12.10
M67 (NGC 2682)	9.80	9.80	9.60	9.45	9.65	9.80

log t, E(B-V) and [Fe/H] fixed, only
Distance modulus determined

Value from the
literature



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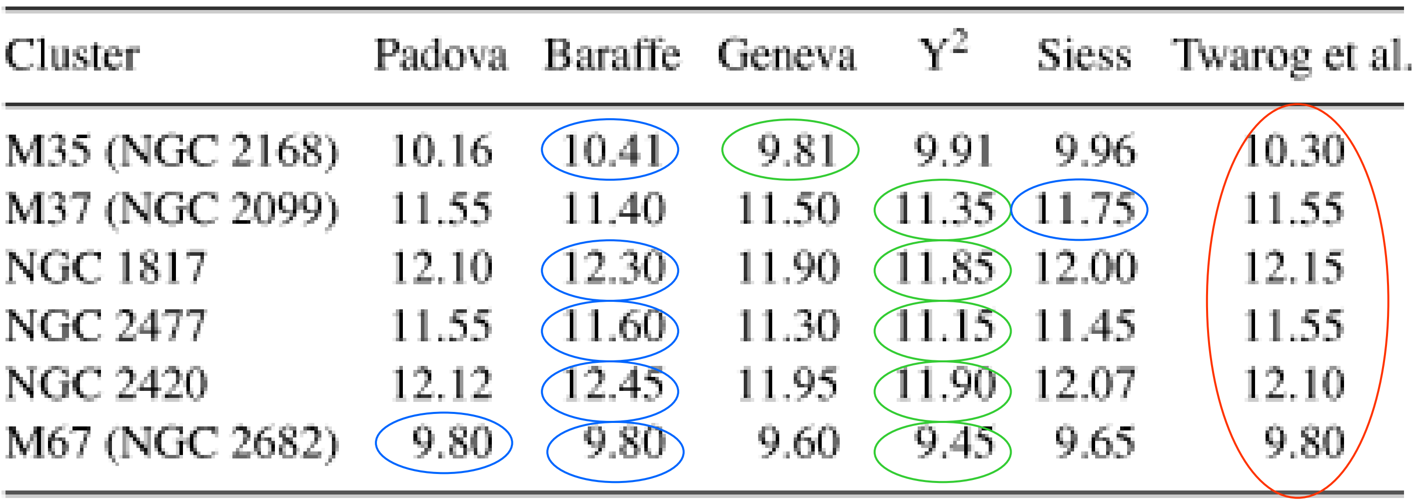
NGC 1817	12.10	12.30	11.90	11.85	12.00	12.15
NGC 2477	11.55	11.60	11.30	11.15	11.45	11.55
NGC 2420	12.12	12.45	11.95	11.90	12.07	12.10
M67 (NGC 2682)	9.80	9.80	9.60	9.45	9.65	9.80

Transformation in distances [pc]

- M35: 1148 [916,1208]; -20% +5%
- M37: 2042 [1905,2239]; -7% +10%
- NGC 1817: 2692 [2344,2884]; -13% +7%
- NGC 2477: 2042 [1698,2089]; -17% +2%
- NGC 2420: 2630 [2399,3090]; -9% +17%
- M67: 912 [776,912]; -15% +0%
- Mean values: -13(5)% +7(6)%, for one free parameter!



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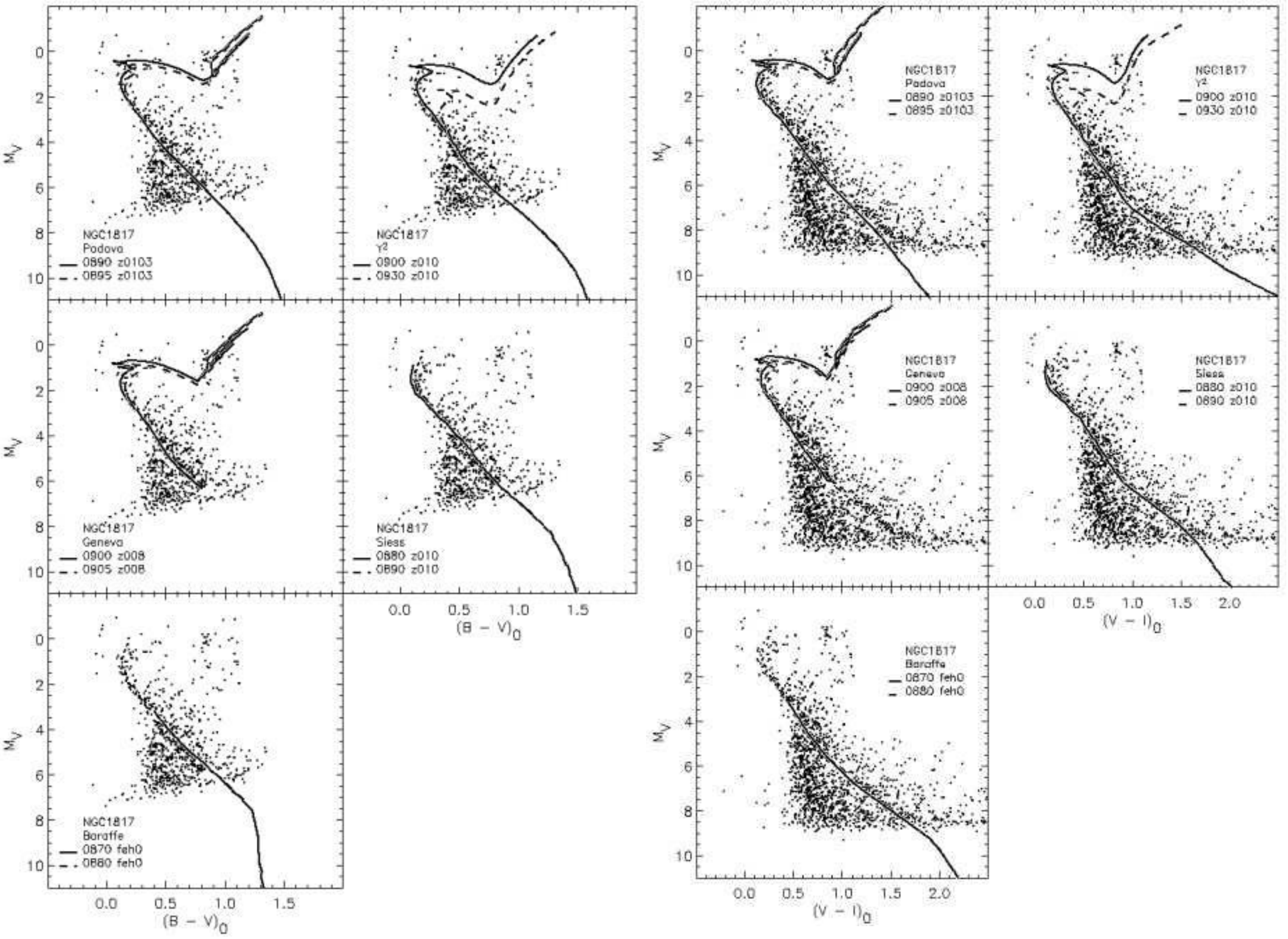
NGC 2477	11.55	11.60	11.30	11.15	11.45	11.55
NGC 2420	12.12	12.45	11.95	11.90	12.07	12.10
M67 (NGC 2682)	9.80	9.80	9.60	9.45	9.65	9.80

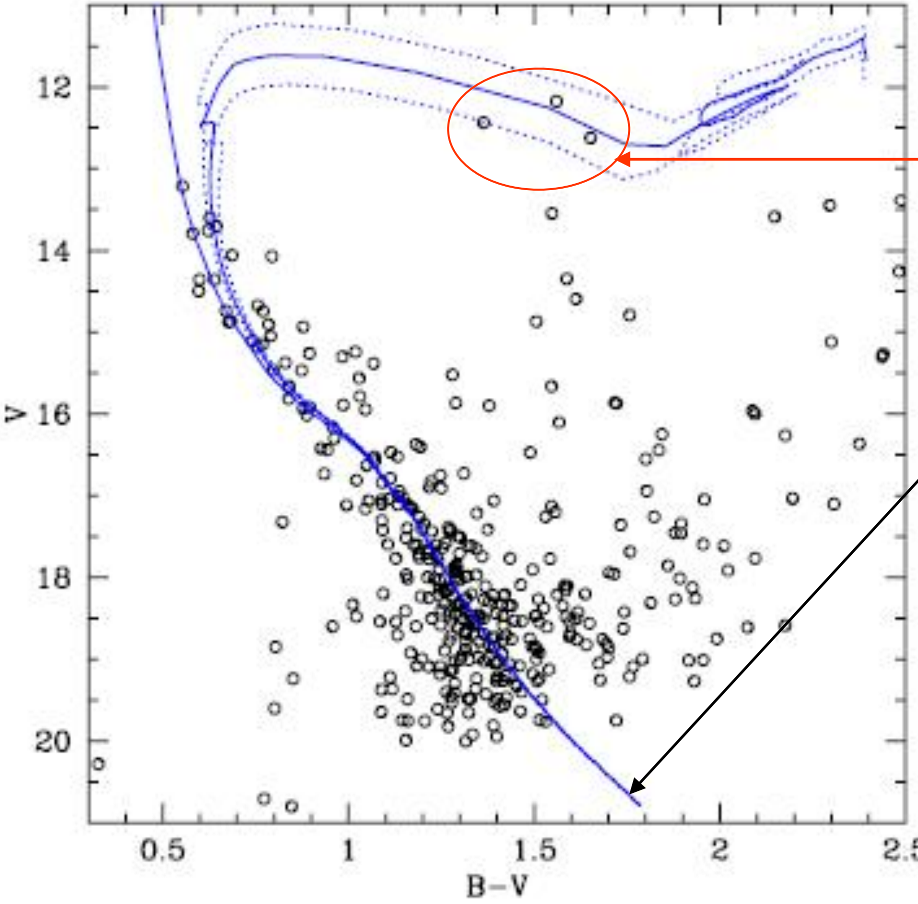
In a statistical point-of-view: significant

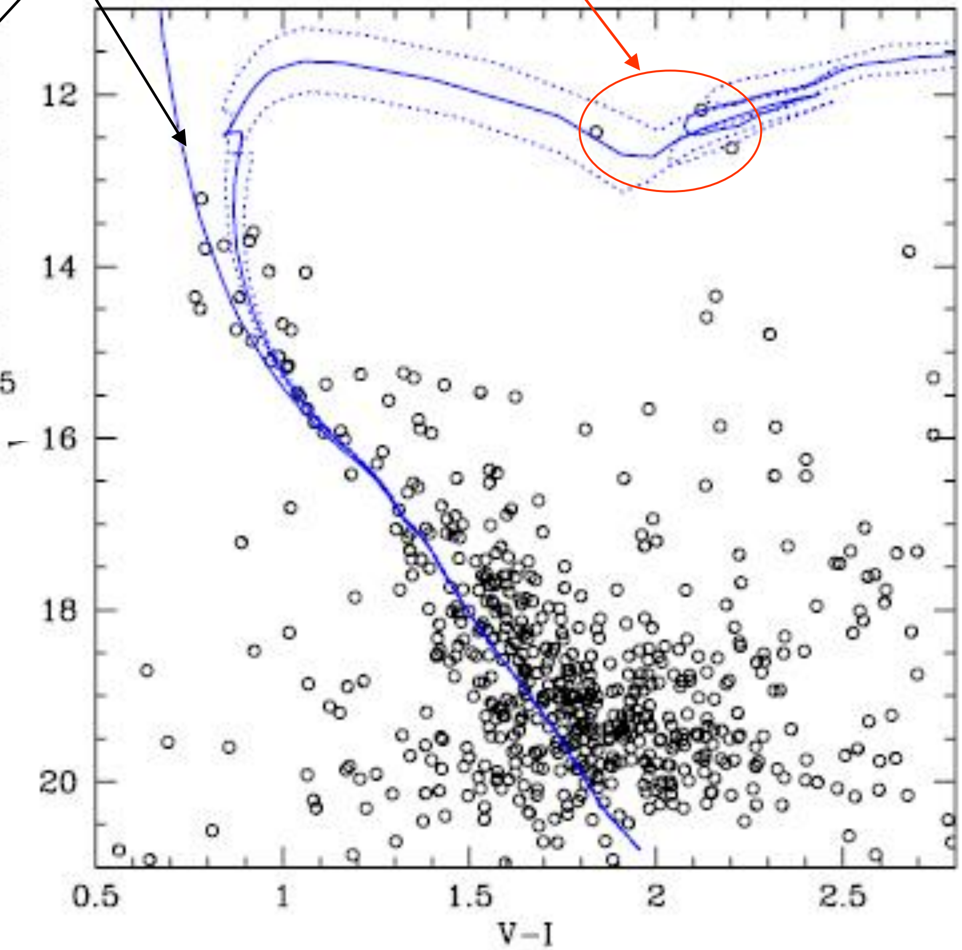
For a given reddening, metallicity and age, the isochrones by Baraffe et al. yield significantly brighter and Yi et al. significantly fainter absolute magnitudes .

In addition, the isochrones by Siess et al. do not reproduce the location of the Sun correctly.



Grocholski & Sarajedini, 2003, MNRAS, 345, 1015





Age determination ONLY based on these three stars

log t = **7.0**

Isochrones for [Z] = 0.040 and log t = 8.0, 8.1 und 8.2

Result: $t = 130^{+40}_{-30}$ Myr
E(B-V) = 0.75(5) mag
$V - M_V$ = 14.00(25) mag

Automatic Methods

Jorgensen & Lindegren, 2005, A&A, 436, 127

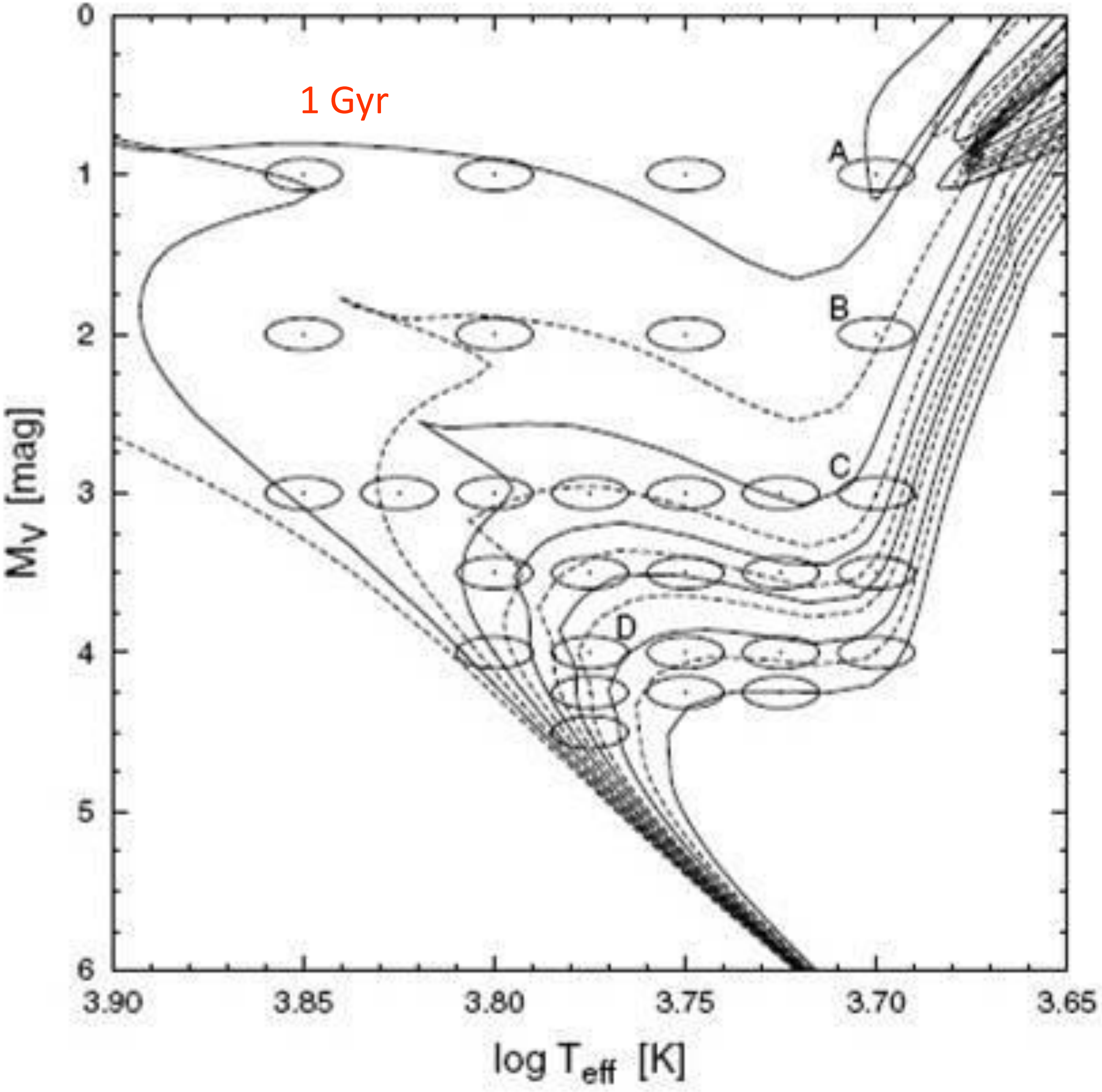
Definition of different „important“ areas (Box) in the CMD. Do this allocation as you like.

Turn-off point, location of the red giant clump, and so on.

Count the number of stars in each box.

Warning: you always „lose“ stars because of discrete boxes.

Only for t > 300 Myr



Other methods

- https://github.com/hektor-monteiro/OCFit
- https://asteca.readthedocs.io/en/latest/
- An et al., 2007, ApJ, 655, 233
- Buckner & Froebrich, 2013, MNRAS, 436, 1465
- Fernandes et al., 2012, A&A, 541, A95
- Frayn & Gilmore, 2003, MNRAS, 339, 887
- Kharchenko et al., 2005, A&A, 438, 1136
- Monteiro et al., 2010, A&A, 516, A2
- Oliveira et al., 2013, A&A, 557, A14
- Pinsonneault et al., 2003, ApJ, 598, 588

Metallicity - Basics

- Metallicity as [X:Y:Z]
- X = Hydrogen
- Y = Helium
- Z = „the rest“

$$X \equiv \frac{m_H}{M} \qquad Y \equiv \frac{m_{He}}{M} \qquad Z = \sum_{i>He} \frac{m_i}{M} = 1 - X - Y$$

Metallicity - designations

- In the literature you will find
  - [Z]
  - [Fe/H]
  - [M/H]
  - [Element 1 / Element 2]
- Relations for the transformation are necessary

$$[\mathrm{Fe/H}] = \log_{10}\left(\frac{N_{\mathrm{Fe}}}{N_{\mathrm{H}}}\right)_{\mathrm{star}} - \log_{10}\left(\frac{N_{\mathrm{Fe}}}{N_{\mathrm{H}}}\right)_{\mathrm{sun}}$$

$$[\mathrm{O/Fe}] = \log_{10}\left(\frac{N_{\mathrm{O}}}{N_{\mathrm{Fe}}}\right)_{\mathrm{star}} - \log_{10}\left(\frac{N_{\mathrm{O}}}{N_{\mathrm{Fe}}}\right)_{\mathrm{sun}}$$

$$= \left[\log_{10}\left(\frac{N_{\mathrm{O}}}{N_{\mathrm{H}}}\right)_{\mathrm{star}} - \log_{10}\left(\frac{N_{\mathrm{O}}}{N_{\mathrm{H}}}\right)_{\mathrm{sun}}\right] - \left[\log_{10}\left(\frac{N_{\mathrm{Fe}}}{N_{\mathrm{H}}}\right)_{\mathrm{star}} - \log_{10}\left(\frac{N_{\mathrm{Fe}}}{N_{\mathrm{H}}}\right)_{\mathrm{sun}}\right]$$

Metallicity – designations

$$[\mathrm{M/H}] = \log_{10}\left(\frac{N_\mathrm{M}}{N_\mathrm{H}}\right)_\mathrm{star} - \log_{10}\left(\frac{N_\mathrm{M}}{N_\mathrm{H}}\right)_\mathrm{sun}$$

$$\log_{10}\left(\frac{Z/X}{Z_\mathrm{sun}/X_\mathrm{sun}}\right) = [\mathrm{M/H}]$$

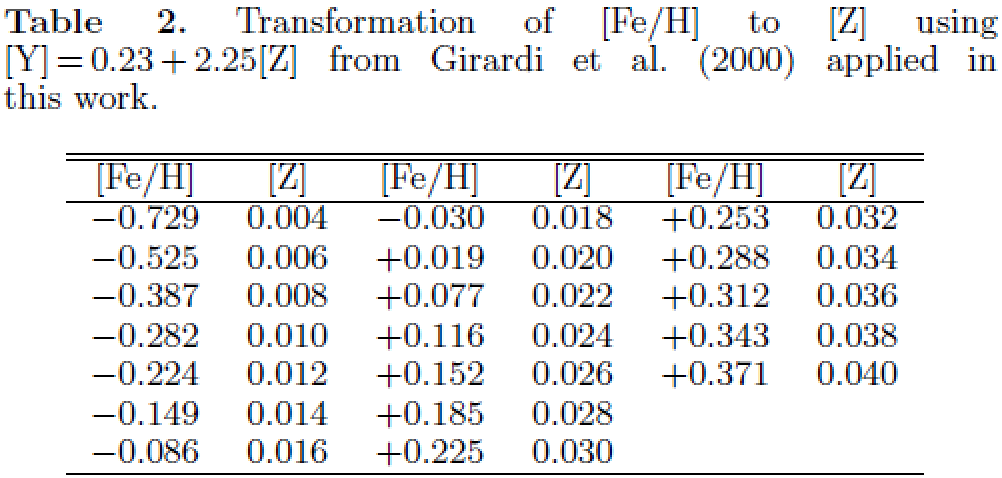


Table 2. Transformation of [Fe/H] to [Z] using $[\mathrm{Y}] = 0.23 + 2.25[\mathrm{Z}]$ from Girardi et al. (2000) applied in this work.

[Fe/H]	[Z]	[Fe/H]	[Z]	[Fe/H]	[Z]
−0.729	0.004	−0.030	0.018	+0.253	0.032
−0.525	0.006	+0.019	0.020	+0.288	0.034
−0.387	0.008	+0.077	0.022	+0.312	0.036
−0.282	0.010	+0.116	0.024	+0.343	0.038
−0.224	0.012	+0.152	0.026	+0.371	0.040
−0.149	0.014	+0.185	0.028		
−0.086	0.016	+0.225	0.030		

Metallicity - designations

- [dex], e.g. [Fe/H] = -0,5 dex

dex	factor	dex	factor
-2	0,01	0,1	1,26
-1,5	0,03	0,2	1,58
-1	0,10	0,3	2,00
-0,9	0,13	0,4	2,51
-0,8	0,16	0,5	3,16
-0,7	0,20	0,6	3,98
-0,6	0,25	0,7	5,01
-0,5	0,32	0,8	6,31
-0,4	0,40	0,9	7,94
-0,3	0,50	1	10,00
-0,2	0,63	1,5	31,62
-0,1	0,79	2	100,00

The Sun as standard star

- „Our“ standard star for the normalisation of the metallicity is the Sun
- We define:
  - Mass
  - Luminosity = absolute (bolometric) magnitude
  - Temperature = spectral type = color
  - Age
  - Chemical composition
  - Internal structure (rotation, magnetic field, convection, diffusion, pulsation, …)

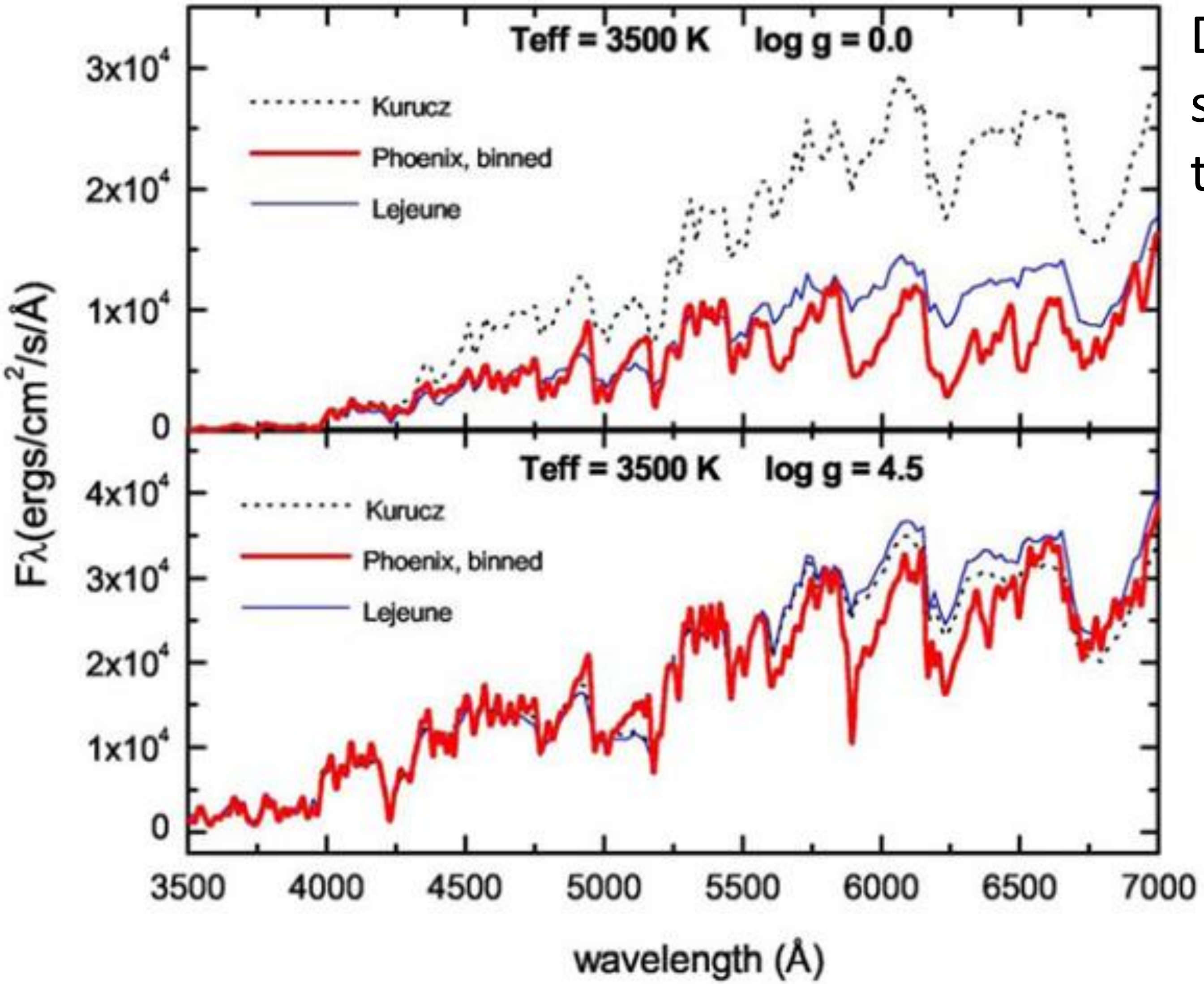
Abundance analysis - Sun

- *Review article:* Asplund et al., 2009, Annual Review of Astronomy & Astrophysics, 47, 481
- Ingredients:
  - Stellar atmosphere
  - Atomic line data
  - High resolution spectra
  - Analysis method
  - Starting parameter
- Gray, 2005, The Observation and Analysis of Stellar Photospheres, Cambridge University Press

Stellar atmospheres

- **ATLAS**, http://atmos.obspm.fr/
- **MARCS**, http://marcs.astro.uu.se/
- **NEMO**, http://www.univie.ac.at/nemo
- **PHOENIX**, http://www.hs.uni-hamburg.de/EN/For/ThA/phoenix/index.html
- **TLUSTY**, http://nova.astro.umd.edu/
- **Stellar Atmospheres Software**, http://www.arm.ac.uk/~csj/software_store/
- **Workshop**: http://astro.physics.muni.cz/events/spec_ws_2017/

Stellar atmospheres



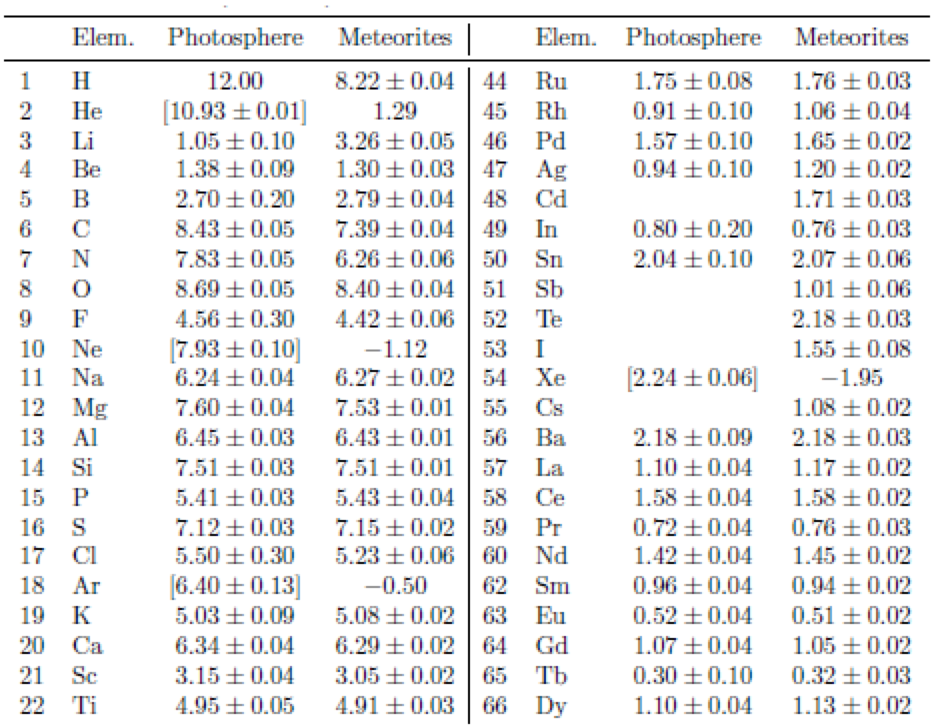
Different synthesized stellar spectra “for the same star“

Abundance - Sun

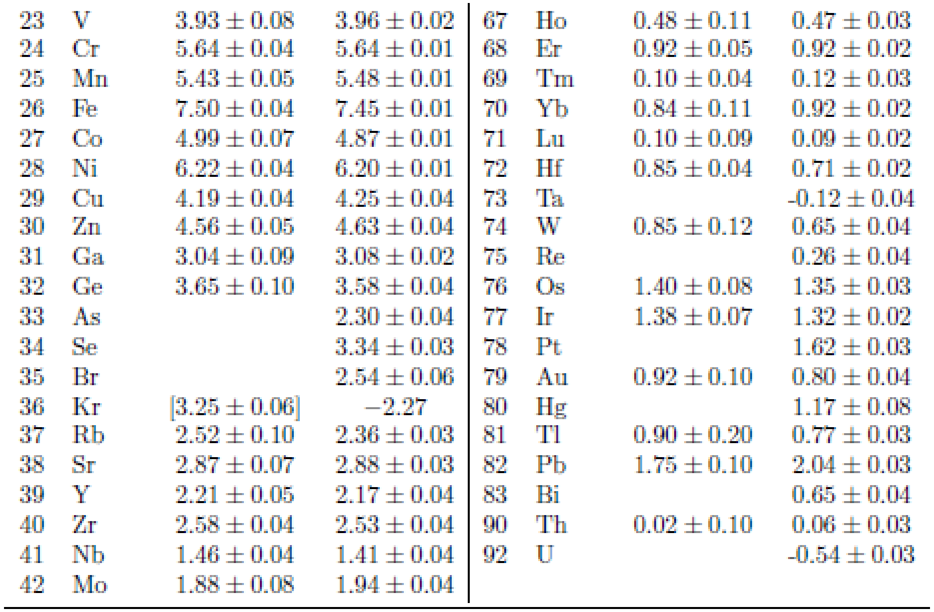
- Problems with
  - Hydrogen
  - Helium
  - Elements with only a few lines
  - Elements with only weak lines
- LTE versus NLTE (Local Thermodynamic Equilibrium)

Abundance - Sun

Asplund et al.

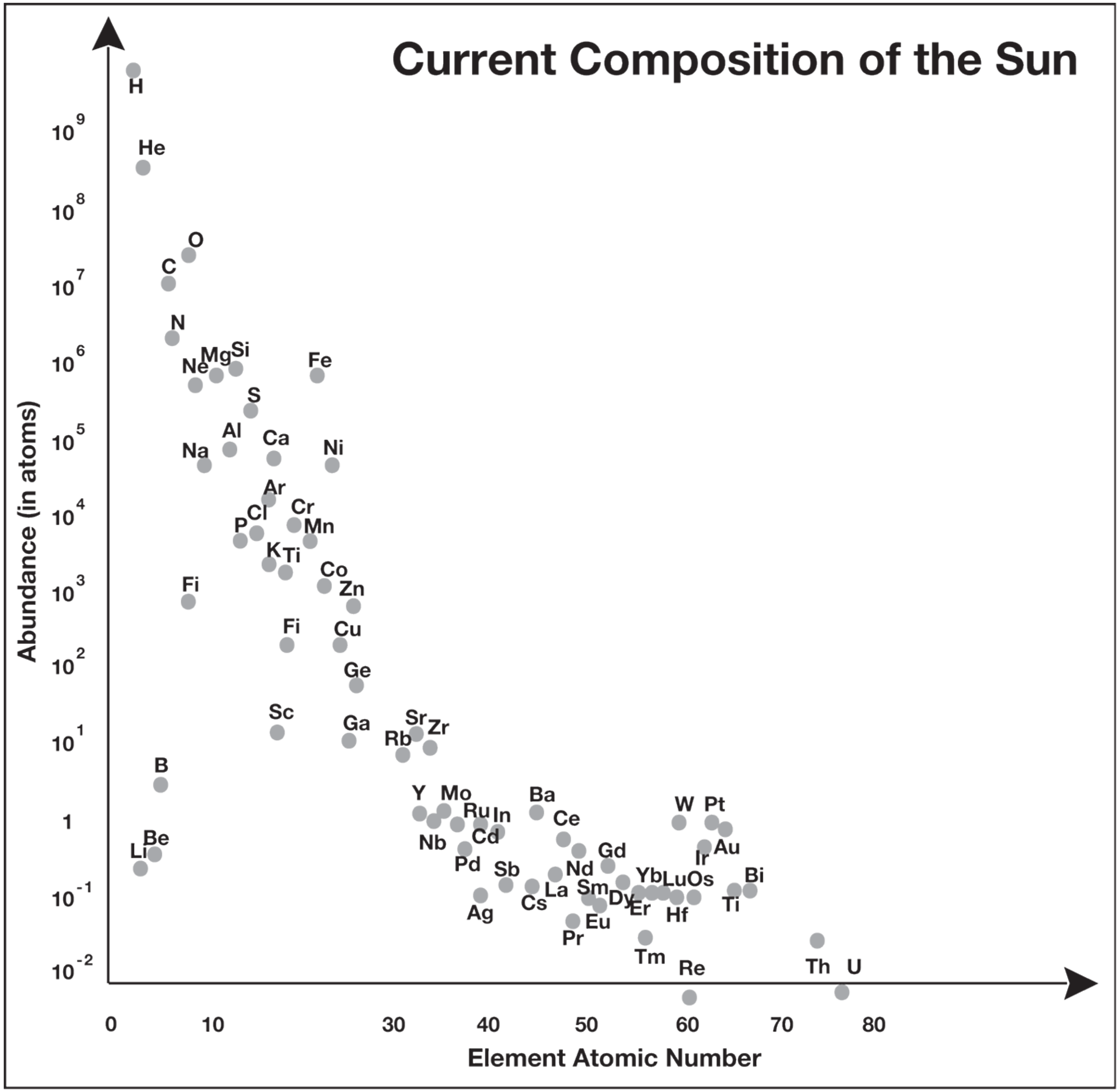


	Elem.	Photosphere	Meteorites		Elem.	Photosphere	Meteorites
1	H	12.00	8.22 ± 0.04	44	Ru	1.75 ± 0.08	1.76 ± 0.03
2	He	[10.93 ± 0.01]	1.29	45	Rh	0.91 ± 0.10	1.06 ± 0.04
3	Li	1.05 ± 0.10	3.26 ± 0.05	46	Pd	1.57 ± 0.10	1.65 ± 0.02
4	Be	1.38 ± 0.09	1.30 ± 0.03	47	Ag	0.94 ± 0.10	1.20 ± 0.02
5	B	2.70 ± 0.20	2.79 ± 0.04	48	Cd		1.71 ± 0.03
6	C	8.43 ± 0.05	7.39 ± 0.04	49	In	0.80 ± 0.20	0.76 ± 0.03
7	N	7.83 ± 0.05	6.26 ± 0.06	50	Sn	2.04 ± 0.10	2.07 ± 0.06
8	O	8.69 ± 0.05	8.40 ± 0.04	51	Sb		1.01 ± 0.06
9	F	4.56 ± 0.30	4.42 ± 0.06	52	Te		2.18 ± 0.03
10	Ne	[7.93 ± 0.10]	−1.12	53	I		1.55 ± 0.08
11	Na	6.24 ± 0.04	6.27 ± 0.02	54	Xe	[2.24 ± 0.06]	−1.95
12	Mg	7.60 ± 0.04	7.53 ± 0.01	55	Cs		1.08 ± 0.02
13	Al	6.45 ± 0.03	6.43 ± 0.01	56	Ba	2.18 ± 0.09	2.18 ± 0.03
14	Si	7.51 ± 0.03	7.51 ± 0.01	57	La	1.10 ± 0.04	1.17 ± 0.02
15	P	5.41 ± 0.03	5.43 ± 0.04	58	Ce	1.58 ± 0.04	1.58 ± 0.02
16	S	7.12 ± 0.03	7.15 ± 0.02	59	Pr	0.72 ± 0.04	0.76 ± 0.03
17	Cl	5.50 ± 0.30	5.23 ± 0.06	60	Nd	1.42 ± 0.04	1.45 ± 0.02
18	Ar	[6.40 ± 0.13]	−0.50	62	Sm	0.96 ± 0.04	0.94 ± 0.02
19	K	5.03 ± 0.09	5.08 ± 0.02	63	Eu	0.52 ± 0.04	0.51 ± 0.02
20	Ca	6.34 ± 0.04	6.29 ± 0.02	64	Gd	1.07 ± 0.04	1.05 ± 0.02
21	Sc	3.15 ± 0.04	3.05 ± 0.02	65	Tb	0.30 ± 0.10	0.32 ± 0.03
22	Ti	4.95 ± 0.05	4.91 ± 0.03	66	Dy	1.10 ± 0.04	1.13 ± 0.02



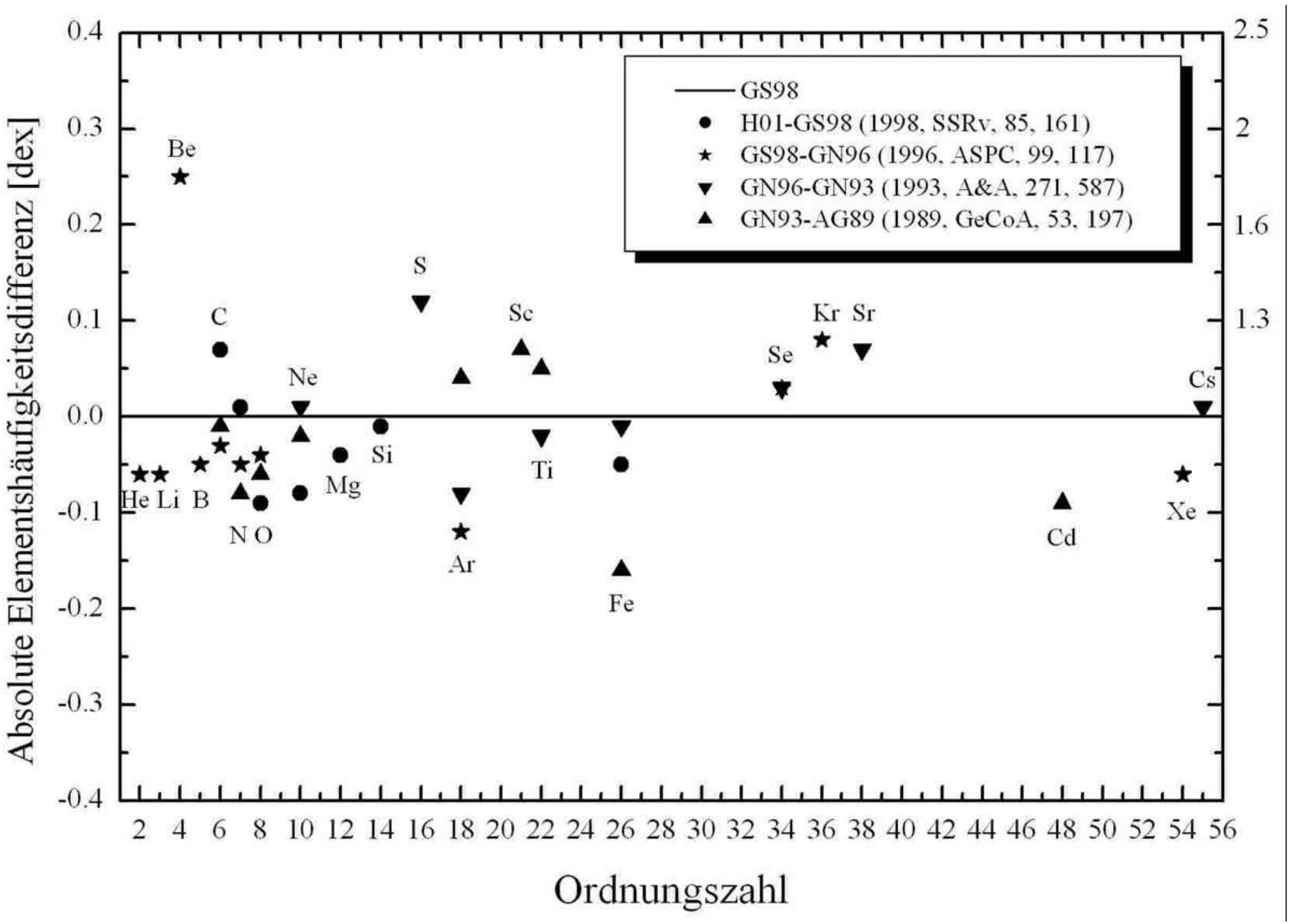
23	V	3.93 ± 0.08	3.96 ± 0.02	67	Ho	0.48 ± 0.11	0.47 ± 0.03
24	Cr	5.64 ± 0.04	5.64 ± 0.01	68	Er	0.92 ± 0.05	0.92 ± 0.02
25	Mn	5.43 ± 0.05	5.48 ± 0.01	69	Tm	0.10 ± 0.04	0.12 ± 0.03
26	Fe	7.50 ± 0.04	7.45 ± 0.01	70	Yb	0.84 ± 0.11	0.92 ± 0.02
27	Co	4.99 ± 0.07	4.87 ± 0.01	71	Lu	0.10 ± 0.09	0.09 ± 0.02
28	Ni	6.22 ± 0.04	6.20 ± 0.01	72	Hf	0.85 ± 0.04	0.71 ± 0.02
29	Cu	4.19 ± 0.04	4.25 ± 0.04	73	Ta		-0.12 ± 0.04
30	Zn	4.56 ± 0.05	4.63 ± 0.04	74	W	0.85 ± 0.12	0.65 ± 0.04
31	Ga	3.04 ± 0.09	3.08 ± 0.02	75	Re		0.26 ± 0.04
32	Ge	3.65 ± 0.10	3.58 ± 0.04	76	Os	1.40 ± 0.08	1.35 ± 0.03
33	As		2.30 ± 0.04	77	Ir	1.38 ± 0.07	1.32 ± 0.02
34	Se		3.34 ± 0.03	78	Pt		1.62 ± 0.03
35	Br		2.54 ± 0.06	79	Au	0.92 ± 0.10	0.80 ± 0.04
36	Kr	[3.25 ± 0.06]	−2.27	80	Hg		1.17 ± 0.08
37	Rb	2.52 ± 0.10	2.36 ± 0.03	81	Tl	0.90 ± 0.20	0.77 ± 0.03
38	Sr	2.87 ± 0.07	2.88 ± 0.03	82	Pb	1.75 ± 0.10	2.04 ± 0.03
39	Y	2.21 ± 0.05	2.17 ± 0.04	83	Bi		0.65 ± 0.04
40	Zr	2.58 ± 0.04	2.53 ± 0.04	90	Th	0.02 ± 0.10	0.06 ± 0.03
41	Nb	1.46 ± 0.04	1.41 ± 0.04	92	U		-0.54 ± 0.03
42	Mo	1.88 ± 0.08	1.94 ± 0.04				

Abundance - Sun



Asplund et al.

Abundance - Sun



PhD thesis – U. Heiter

Abundance - Sun

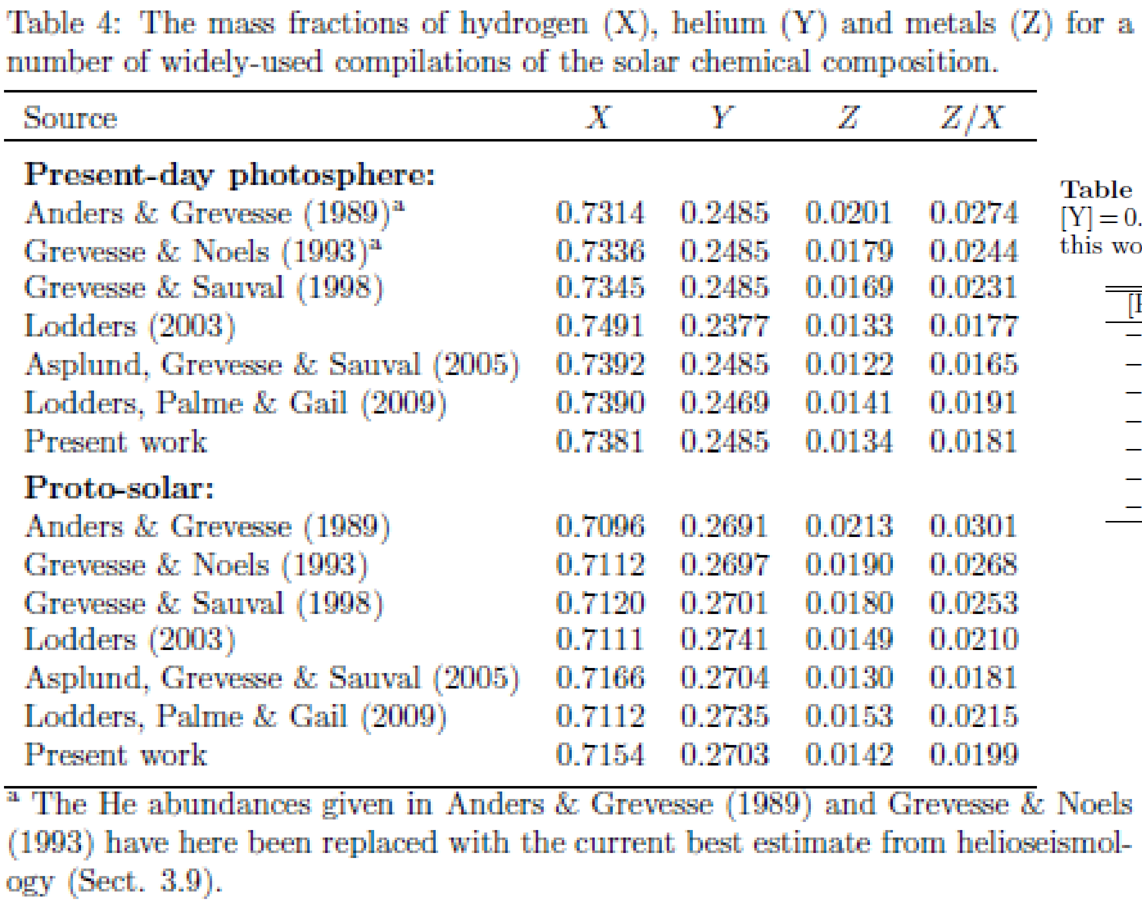
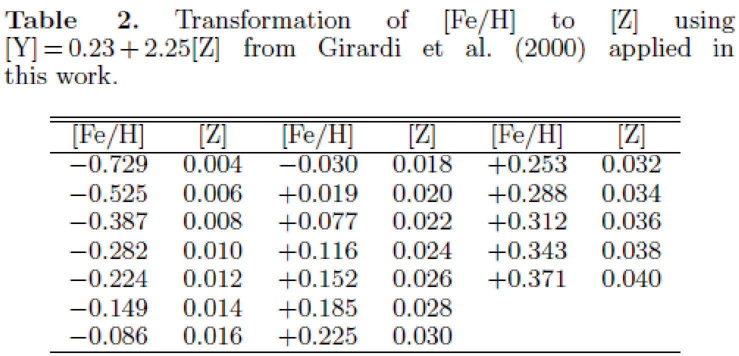


Table 4: The mass fractions of hydrogen (X), helium (Y) and metals (Z) for a number of widely-used compilations of the solar chemical composition.

Source	X	Y	Z	Z/X
Present-day photosphere:				
Anders & Grevesse (1989)[a]	0.7314	0.2485	0.0201	0.0274
Grevesse & Noels (1993)[a]	0.7336	0.2485	0.0179	0.0244
Grevesse & Sauval (1998)	0.7345	0.2485	0.0169	0.0231
Lodders (2003)	0.7491	0.2377	0.0133	0.0177
Asplund, Grevesse & Sauval (2005)	0.7392	0.2485	0.0122	0.0165
Lodders, Palme & Gail (2009)	0.7390	0.2469	0.0141	0.0191
Present work	0.7381	0.2485	0.0134	0.0181
Proto-solar:				
Anders & Grevesse (1989)	0.7096	0.2691	0.0213	0.0301
Grevesse & Noels (1993)	0.7112	0.2697	0.0190	0.0268
Grevesse & Sauval (1998)	0.7120	0.2701	0.0180	0.0253
Lodders (2003)	0.7111	0.2741	0.0149	0.0210
Asplund, Grevesse & Sauval (2005)	0.7166	0.2704	0.0130	0.0181
Lodders, Palme & Gail (2009)	0.7112	0.2735	0.0153	0.0215
Present work	0.7154	0.2703	0.0142	0.0199

[a] The He abundances given in Anders & Grevesse (1989) and Grevesse & Noels (1993) have here been replaced with the current best estimate from helioseismology (Sect. 3.9).



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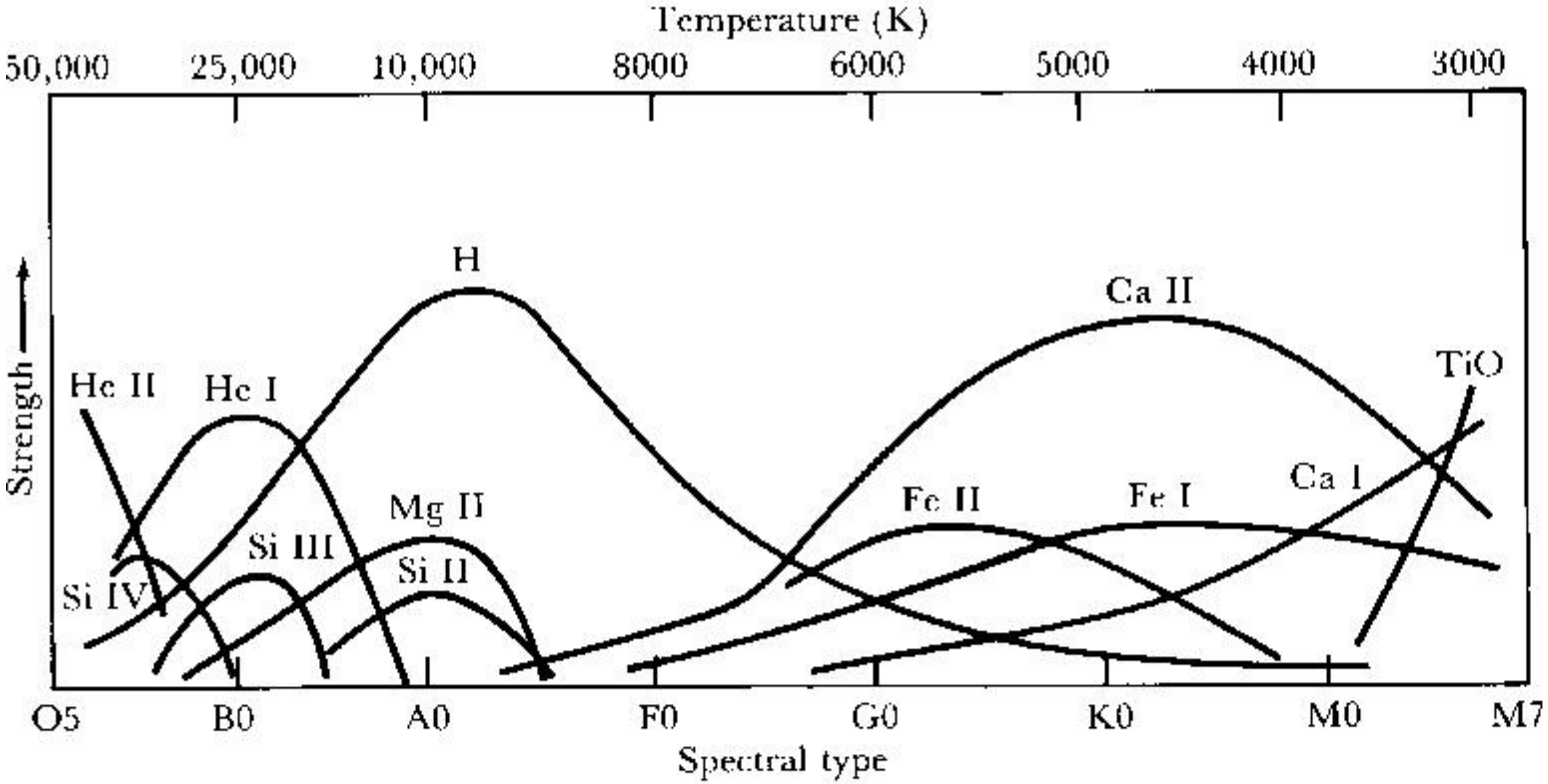
−0.149	0.014	+0.185	0.028		
−0.086	0.016	+0.225	0.030		

Asplund et al.

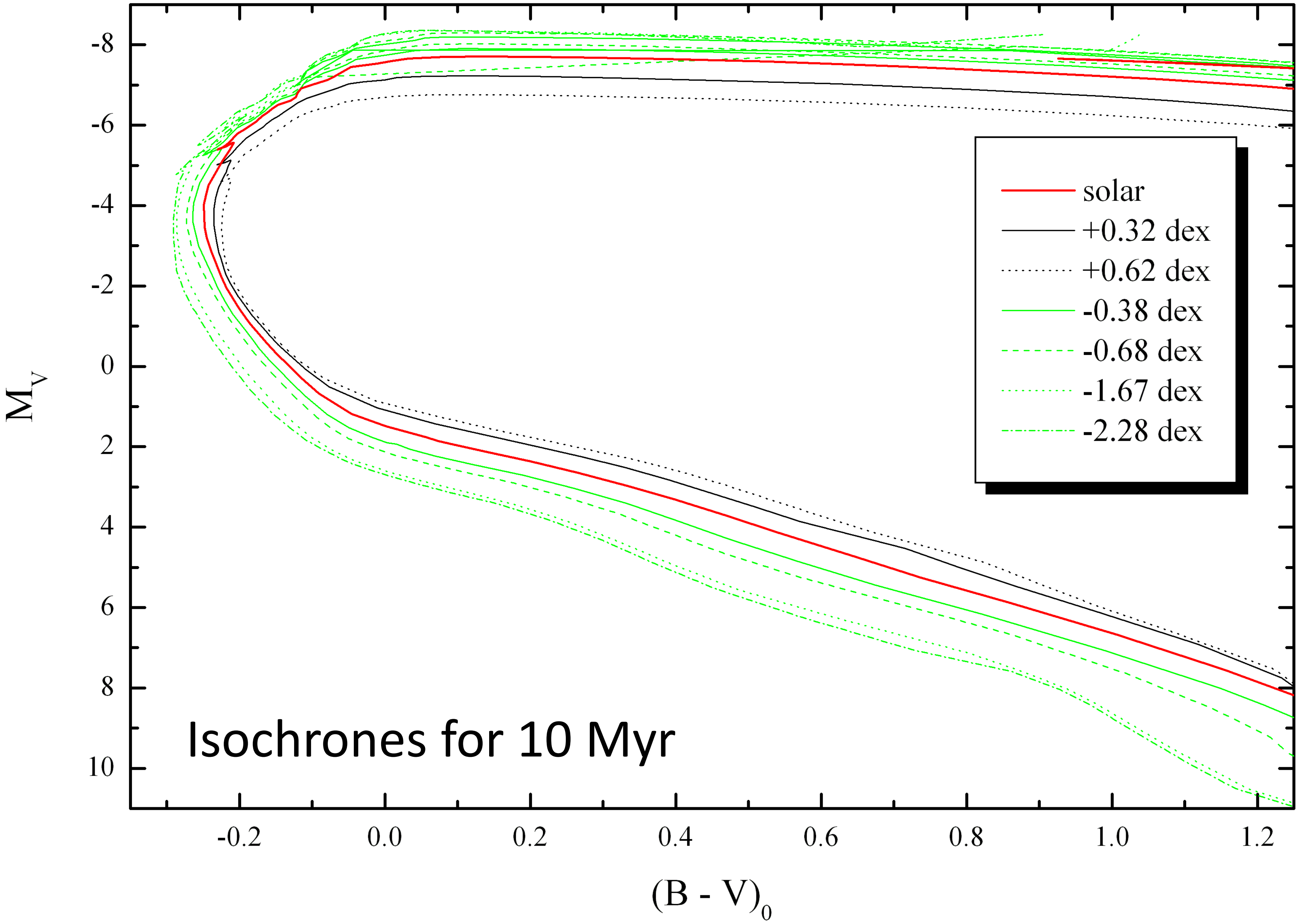
Determination of the metallicity

- The determination of the metallicity can be done in three ways:
  1. Spectroscopic abundance analysis
  2. Fitting of isochrones
  3. Photometric calibrations
- ESO- Gaia survey:
  https://www.gaia-eso.eu/

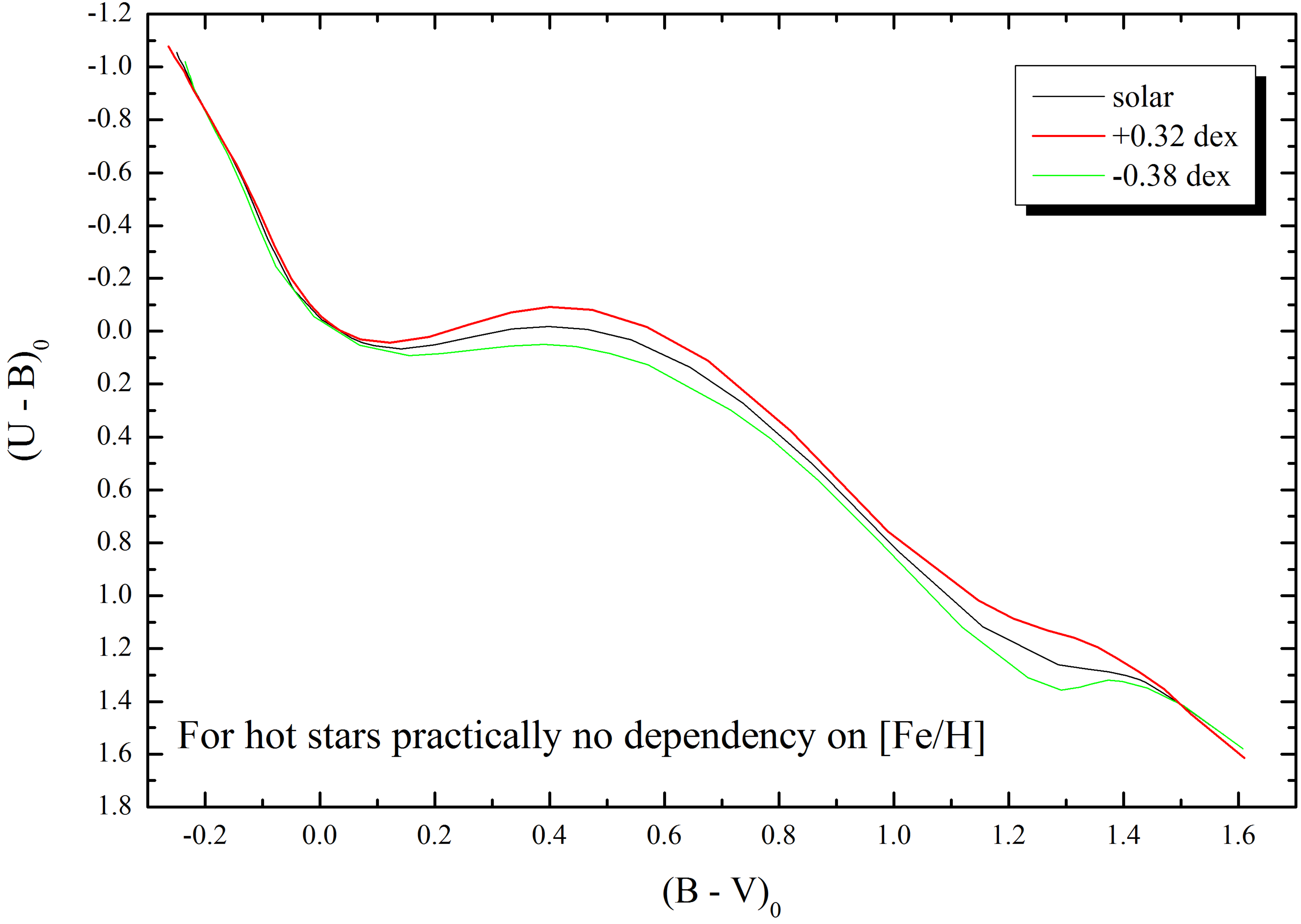
„Metalls“ in stars



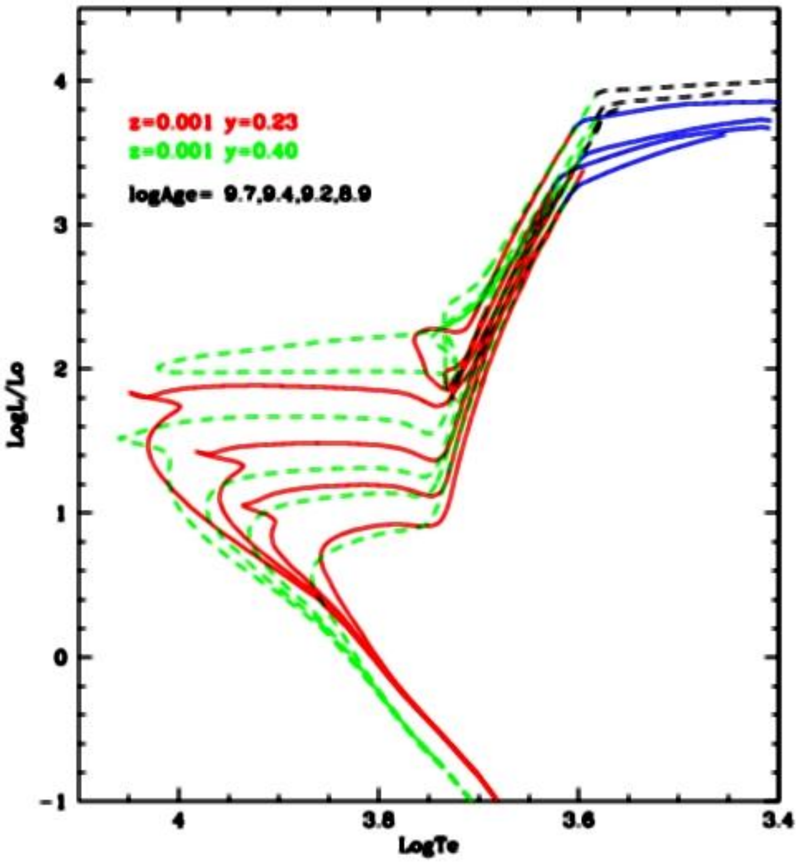
Metallicity => different opacity



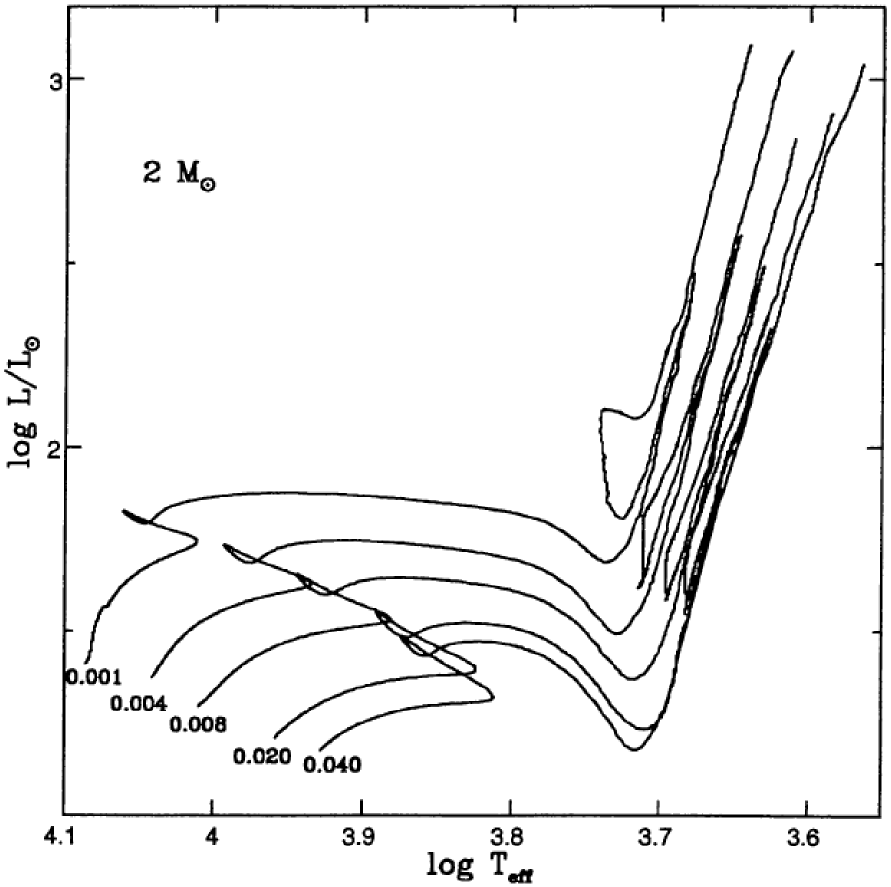
Isochrones for 10 Myr


solar
+0.32 dex
-0.38 dex
For hot stars practically no dependency on [Fe/H]
(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
1.2
1.4
1.6
1.8
-0.2
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6

Metallicity - isochrones



Different He abundances – [Z] constant



Schaller et al., 1993, A&AS, 101, 415