HIPPARCOS SUBDWARFS AND GLOBULAR CLUSTERS: TOWARDS RELIABLE ABSOLUTE AGES

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ABSTRACT

The distance and age of the key globular cluster M92 are determined with Hipparcos field subdwarfs. [Fe/H] values for subdwarfs we re measured with the Coravel spectrometer. The distance modulus of M92 is obtained by fitting the cluster sequence to subdwarfs of a similar metallicity, and the age by comparison of the turnoff magnitude with up-to-date evolution models. Particular attention is given to systematic and selection biases, and to the effect of binaries. Field subdwarfs evolved past the turnoff stage are also considered.

Our best estimate of the distance modulus of M92 is $\mu_0 = 14.61 \pm 0.08$ mag, using 17 Hipparcos subdwarfs with [Fe/H]< -1.8. The age obtained is 14 ± 1.2 Gyr, implying an age of at least 14 Gyr for the Universe. The value of the small colour shift needed in the models to fit the M92 sequence is confirmed with an independent set of intermediate-metallicity Hipparcos subdwarfs.

Key words: globular clusters; subdwarfs; ages (globular clusters, Universe).

1. INTRODUCTION

The dependence of turnoff luminosity on age for globular clusters (GC) is a very robust prediction of stellar evolution models. It is directly related to main-sequence lifetimes for $\sim 1 M_\odot$ stars, and avoids the delicate problems associated with the model temperature and colour predictions (age from turnoff colour) or with advanced stages of evolution (age from horizontal-branch position).

Up to now, the main obstacle to the application of the turnoff luminosity method to determine reliable absolute ages for GCs has been the uncertain definition of the subdwarf intrinsic luminosity scale. Hipparcos parallaxes for nearby subdwarfs now allow a new calibration of this scale. GC sequences can be directly fitted to local subdwarfs of known distances and similar metallicities, and their distance moduli can be determined independently of any model assumption.

We shall focus here on M92 (NGC 6341) as a representative of the oldest GC population. M92 is one of the most metal-poor GC, with a small and uncontroversial value of foreground reddening, a well-known metallicity, and a sequence measured with great accuracy down to $M_V > 8$ mag (Stetson & Harris 1988). It has been recognized by several study of relative ages as among the oldest GCs (Stetson et al. 1996).

2. HIPPARCOS SUBDWARF SAMPLE

The sample on which this study is based is the union of two separate Hipparcos proposals:

– a set of 330 stars previously known to be subdwarf candidates from various sources.

– about 300 stars revealed to be markedly below the solar-metallicity ZAMS according to Hipparcos data.

Coravel[1] [Fe/H] measurements were gathered for most stars in the sample, and pooled with other reliable metallicity determinations for subdwarfs (Schuster & Nissen 1989, Ryan & Norris 1991, Axer et al. 1994, Carney et al. 1994). The result is a set of 506 subdwarf candidates with good parallax ($\sigma_\pi/\pi <$ 20 per cent), magnitude, colour and [Fe/H] data, from which smaller samples can be selected for specific studies.

3. CORAVEL [FE/H] DETERMINATION

The cross-correlation function equivalent width (denoted W) given by the radial velocity scanner Coravel is a tight function of T_{eff} and [Fe/H] for dwarfs. For F dwarfs, the determination of [Fe/H] from W

[1]The Coravel radial velocity scanner is described in Baranne et al. (1979).

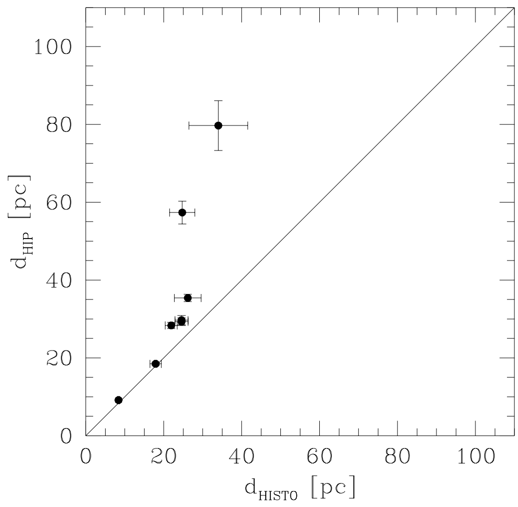


Figure 1. Hipparcos distances compared to previous estimates (from Zinn & West 1981), for the eight subdwarfs most often used to determine the subdwarf luminosity scale. Most distances were importantly underestimated.

was calibrated using the meticulous study of Edvardsson et al. (1993). The resulting dispersion, σ ([Fe/H]$_{\rm Coravel}-$[Fe/H]$_{E93}$), is 0.06 dex if $T_{\rm eff}$ is known independently, or 0.09 dex if the B$-$V colour index is taken as a temperature indicator. These values indicate that the Coravel determination is at least as precise as good spectroscopic values.

For G dwarfs and subdwarfs, the W index is calibrated using the comprehensive study by Carney et al. (1994). The resulting dispersion is higher, $\sigma = 0.17$ dex, probably reflecting the lower accuracy of Carney et al. [Fe/H] values.

Some other subdwarf studies, such as Axer et al. (1994), have advocated significantly more compressed [Fe/H] scales for subdwarfs (i.e. shifted towards higher metallicities). The effect of adopting such a [Fe/H] scale ([Fe/H]$_2$) for our sample is also considered.

4. LUMINOSITY OF VERY METAL-POOR SUBDWARFS

Previously, only 8 to 15 subdwarfs of all metallicities had reliable parallaxes. Even for this small sample, the Hipparcos data reveals important systematic errors (Figure 1). The abundance of very metal-poor subdwarfs in our sample allows a separation into several metallicity intervals, thus reducing the need for shifts in colour to bring all objects to a common [Fe/H] (Figure 2). The data show, for the first time, the position of the turnoff and the subgiant branch *of the field subdwarfs*. The sequence is especially clear for the most metal-poor stars. These plots provide a very strong constraint on the subdwarf sequence luminosity, the age of field subdwarfs themselves, and the distance to globular clusters.

5. SYSTEMATICS BIASES

Important systematic biases are known to affect luminosities computed from parallax data (see the often-quoted modelisation of Lutz & Kelker 1973, or the elaboration by Smith 1987). Other biases also affect the calculation of the mean luminosity of a set of stars of given intrinsic characteristics.

From Monte Carlo simulations of the whole selection and treatment procedure, we find that the global bias on globular cluster distances from Hipparcos subdwarfs acts in a direction *opposite* to the classic Lutz-Kelker bias. In the specific case of Hipparcos subdwarfs selected with a $\sigma_\pi/\pi <$ lim criteria and fitted to GC sequences, the total bias can be schematically broken down into three components:

1. the classical Lutz-Kelker bias: the interaction of the steep parallax distribution (Figure 3a) with the parallax uncertainties causes a systematic underestimation of luminosity;
2. a luminosity bias favouring brighter stars, arising from the strong dependence of the parallax uncertainty on magnitude in Hipparcos data (Figure 3b);
3. a Lutz-Kelker type bias on [Fe/H]; the interaction of the steep [Fe/H] distribution for subdwarfs (Figure 3c) with the errors on [Fe/H] causes a systematic underestimation of metallicity.

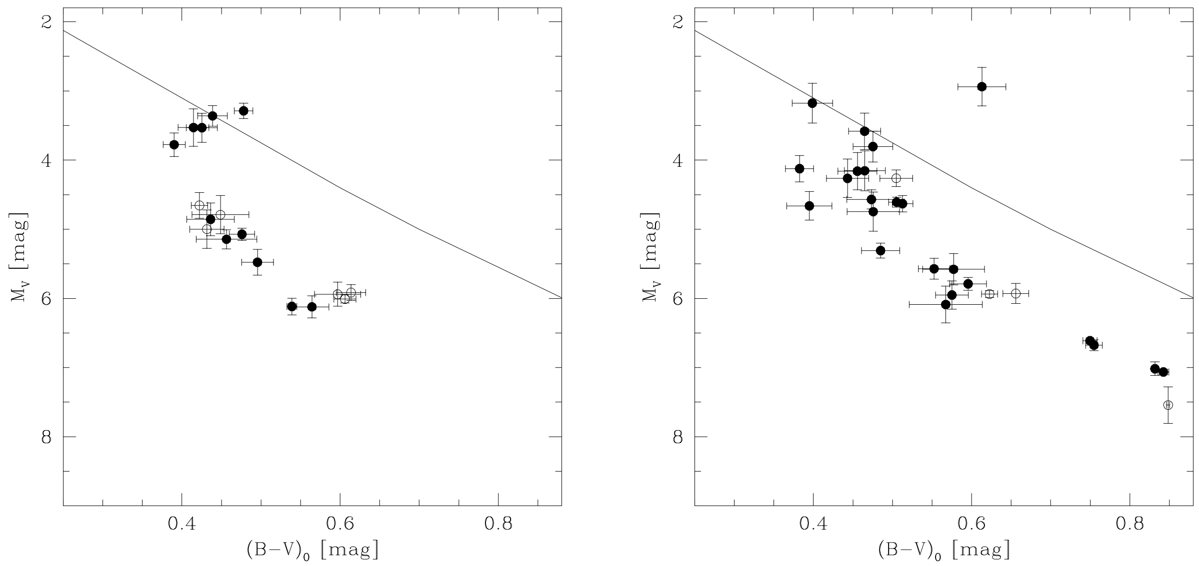
Moreover, (2) and (3) couple strongly, so that at a given [Fe/H] and colour, more metal-rich stars (more numerous and brighter) have a significantly higher probability to be included in the sample than more metal-poor stars, causing a net overestimation of mean luminosity.

From our Monte Carlo simulations, we find a resultant correction of 0.07 mag towards fainter magnitudes for main-sequence subdwarfs, and of 0.11 towards brighter magnitudes for subgiants[2].

6. BINARIES

Several binaries were detected in the sample, either by radial velocity variations or by Hipparcos. Unresolved binaries can be up to 0.75 mag brighter than the single-star sequence, and thus importantly affect the luminosity determination. Along with the usual procedure of removing detected binaries, we also consider the results obtained by applying an average magnitude correction to all detected binaries — a correction calculated from the position of the binary star sequence in the Praesepe cluster from Bolte (1991). This last procedure may be more justified than simply rejecting detected binaries, since it also statistically accounts for undetected binaries remaining in the sample.

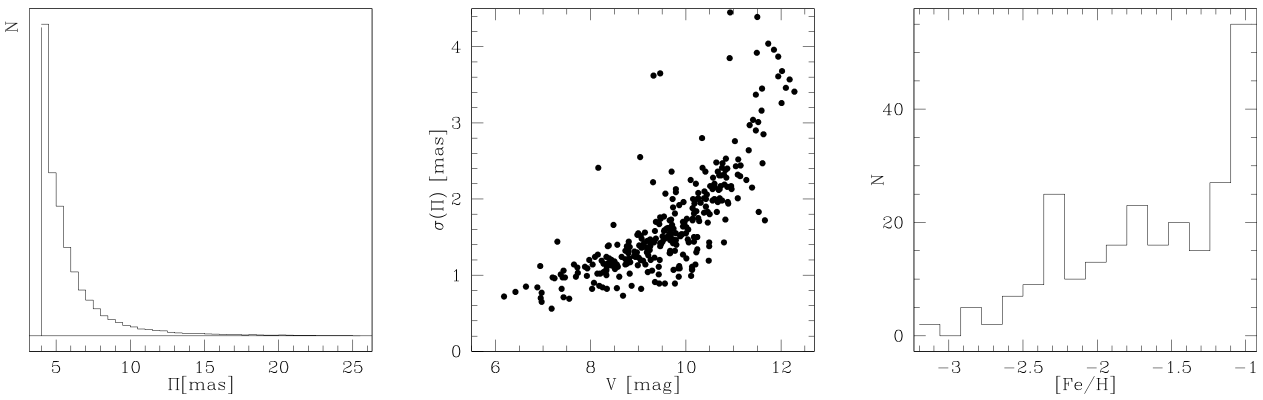
[2]Note that LK-type corrections should still be applied if individual magnitudes are needed. The corrections that we derive are only valid for whole samples, and reflect the average effect of objects excluded by the selection procedure.



(a) Fe/H < −1.8 dex

(b) −1.8 < Fe/H < −1.1 dex

Figure 2. Position in the HR diagram of the most metal-poor subdwarfs, divided in two [Fe/H] intervals. Detected binaries are shown as open symbols. The line is the Hyades sequence.



(a) Distribution of parallaxes for a volume-limited sample.

(b) Dependence of the parallax uncertainty on magnitude for Hipparcos data.

(c) Distribution of metallicity for the subdwarf sample.

Figure 3. Three significant sources of biases.

Table 1. Data for subdwarfs with [Fe/H]$_1$ < -1.8 and σ_π/π <15 per cent. $\delta(B-V)$ is the colour shift used to bring the data to [Fe/H]$_1$ = –2.2.

HIP	Name	$(B-V)_0$	E(B-V)	M_V	σ_{M_V}	[Fe/H]$_1$	[Fe/H]$_2$	$\delta(B-V)$	Binarity Note
14594	HD 19445	0.48	0.01	5.07	0.09	−2.20	−1.96	0.000	C
16404	BD +66 258	0.60	0.06	5.94	0.17	−2.10	−1.87	0.005	C SH
21609	HD 29907	0.61	0.03	5.92	0.12	−2.28	−2.03	−0.004	SB
24316	HD 34328	0.47	0.03	5.15	0.14	−1.88	−1.67	0.014	C
38541	HD 64090	0.62	0.00	6.01	0.06	−1.92	−1.71	0.015	SV
44124	BD −03 2525	0.44	0.04	5.00	0.28	−1.94	−1.73	0.008	SB2
46120	CPD−80 349	0.54	0.02	6.12	0.12	−2.26	−2.01	−0.003	C
48152	HD 84937	0.39	0.01	3.78	0.17	−2.21	−1.97	−0.000	C
60632	HD 108177	0.44	0.00	4.86	0.24	−1.91	−1.70	0.009	C
65201	HD 116064	0.42	0.03	4.66	0.19	−2.39	−2.13	−0.006	H2
68464	HD 122196	0.41	0.05	3.53	0.27	−2.22	−1.98	−0.002	C
72461	BD +26 2606	0.44	0.00	4.79	0.28	−2.58	−2.30	−0.012	SB
73385	HD 132475	0.44	0.06	3.53	0.21	−1.95	−1.74	0.020	C
76976	HD 140283	0.44	0.04	3.29	0.11	−2.41	−2.15	−0.034	C
98532	HD 189558	0.50	0.07	3.36	0.15	−1.84	−1.64	0.064	C
99267	BD +42 3607	0.50	0.01	5.48	0.19	−2.13	−1.90	0.002	C
106924	BD +59 2407	0.58	0.05	6.12	0.16	−1.91	−1.70	0.017	C

Binarity notes – C: constant radial velocity; SB: spectroscopic binary; SB2: double-line spectroscopic binary; SV: possible small radial velocity variations; SH: suspected non-single from Hipparcos catalogue; H2: two components resolved by Hipparcos.

7. DISTANCE OF M92

Figure 4 shows the M92 sequence from Stetson & Harris (1988) fitted to the subdwarfs with [Fe/H]<-1.8, $\sigma_\pi/\pi < 15$ per cent, bias and binarity correction applied, adopting [Fe/H]$= -2.2$ and E(B-V)=0.02 for M92. The data for the 17 stars used in the fit are given in Table 1. The resulting distance modulus for M92 is $\mu_0 = 14.61 \pm 0.08$ mag using corrected binaries, $\mu_0 = 14.68 \pm 0.09$ mag removing binaries (the uncertainty includes uncertainties on the bias and binarity corrections).

With the second metallicity scale, the result is only slightly different: $\mu_0 = 14.58 \pm 0.08$ mag with corrected binaries (the difference is small because the main sequence and subgiant branch subdwarfs have an opposite, compensating dependence of luminosity on [Fe/H]).

The M92 and field subdwarf sequences are in excellent agreement, especially near the subgiant branch, indicating a similar age for M92 and the field subdwarfs.

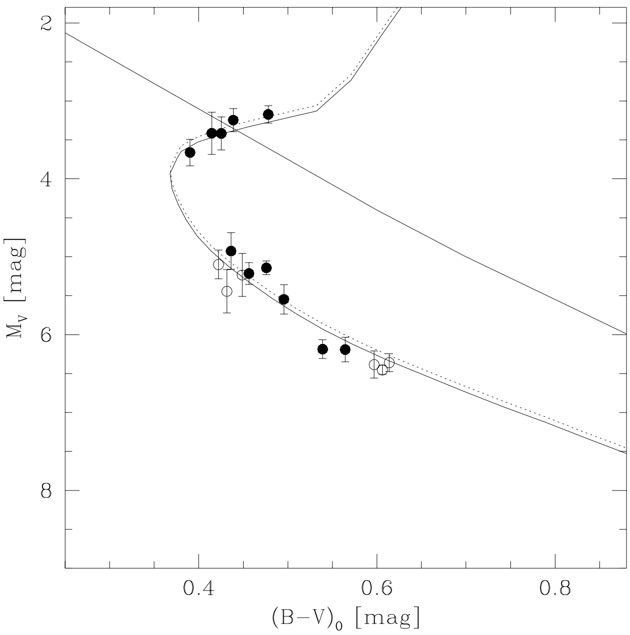


Figure 4. The M92 sequence fitted to the objects of Table 1 (with bias and binarity corrections applied). Solid line: μ_0^{M92} = 14.61 mag, dashed line: μ_0^{M92} = 14.68 mag. The Hyades sequence is also indicated for comparison.

8. AGE OF M92 AND MODEL ISOCHRONES

With the distance obtained above, the age of M92 can be determined by comparison of the magnitude of the turnoff and subgiant branch with model predictions, avoiding any reference to the uncertain model colours or colour-temperature relation. The result depends on the models considered and the bolometric correction used. Several latest generation models (Charbonnel, Lebreton, Vandenberg or Mazzitelli et al. models) give similar results. For instance, with Vandenberg et al. (1997) isochrones, we obtain an age of 14 ± 1.2 Gyr for M92 (Figure 5).

A shift of $\delta(B-V) = +0.012$ is needed to bring the [Fe/H]$= -2.2$ isochrone colours in agreement with the M92 sequence. We have also compared the model isochrones for [Fe/H]$= -1.54$ with the position of intermediate metallicity ($-1.8 <$[Fe/H]< -1.1) subdwarfs with the most precise parallaxes ($\sigma_\pi/\pi < 5$ per cent). In this case (Figure 6 left), a small shift of $\delta(B-V)$=+0.015 must be applied to the model colours. As none of the stars used is common to the first sample of Table 1, this provides an independent confirmation of the colour shift found in the case of

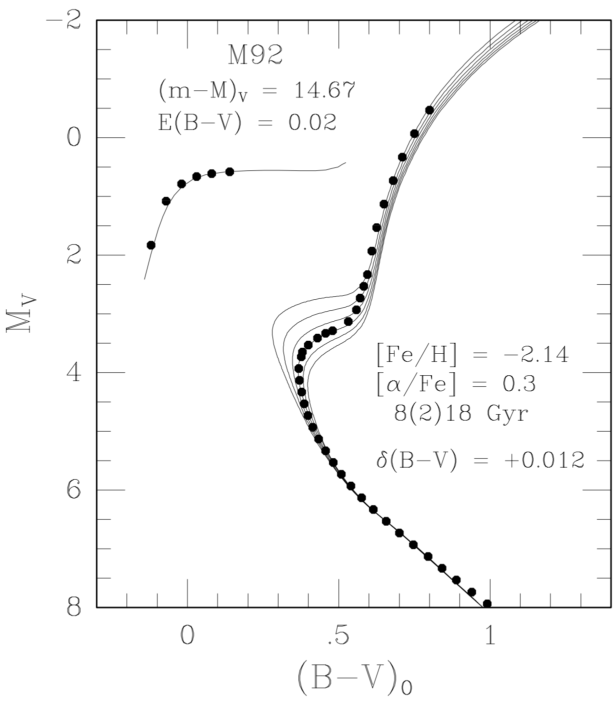


Figure 5. Comparison of the M92 sequence with VandenBerg et al. (1997) model isochrones for the parameters shown, with μ_0^{M92} = 14.61 mag.

M92, and indicates that the model predictions of the luminosity dependence on [Fe/H] are essentially correct.

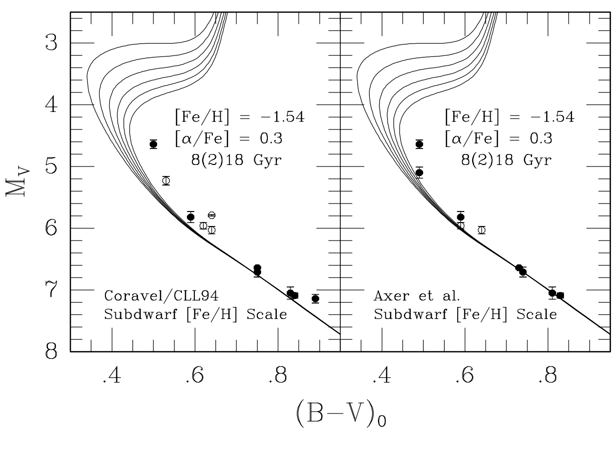


Figure 6. Subdwarfs with $-1.8 <$[Fe/H]< -1.1 and $\sigma_\pi/\pi < 5$ per cent, compared with VandenBerg et al. (1997) model isochrones for [Fe/H] = -1.54, using the two metallicity scales. Detected binaries are shown as open symbols. For the first metallicity scale, a colour shift of $\delta(B-V) = +0.015$ is needed to bring the observed sequence and the models in agreement (no shift is necessary with the second metallicity scale). The position of the leftmost point, HIP 104659, is not understood. It is probably an undetected binary.

Broad limits can be put on the age of the field subdwarfs themselves by direct comparison of the evolved stars with model isochrones (see Figure 7). Ages as low as 11 Gyr or as high as 18 Gyr seem highly improbable given the position of these objects.

Our value for the age of M92 implies an age of at least 14 Gyr for the Universe. This in turn imposes rather low values of H_0 for standard inflation cosmologies (if $\Omega = 1$ and $\Lambda = 0$, then H_0 must be ≤ 48 km s^{-1}Mpc^{-1}), lower than most current estimates (55-80 km s^{-1}Mpc^{-1}, e.g. Ferrarese et al. 1996, Hamuy et al. 1996, Sandage et al. 1996).

9. CONCLUSION

The Hipparcos data for subdwarfs has greatly reduced the uncertainty on GC ages due to the subdwarf luminosity scale, so that the dominant source of error now becomes associated with the stellar model ingredients (of the order of ± 2 Gyr, see for example Vandenberg et al. 1996). However, an agreement on the implication of the Hipparcos subdwarf data still has to be reached. Reid (1997) obtains a much higher distance of $\mu \sim 14.9$ mag for M92, while Fusi Pecci et al. (this volume) arrive at a value intermediate between Reid's and our value. A high distance for M92 would imply a correspondingly younger age, of the order of 11 Gyr, and the surprising result that luminosity is virtually independent of metallicity for the subdwarf sequences below [Fe/H]~ -1.3 dex.

There can be several sources to these differences: number and identity of the calibrators, metallicity scale, treatment of biases, binaries and subgiants, colour and reddening values used. All these points deserve to be re-considered more closely when the Hipparcos Catalogue is available as a whole.

To estimate the remaining uncertainties due to the evolution model ingredients, we are comparing three different sets of model isochrones, from C. Charbonnel, Y. Lebreton and D. VandenBerg. From confrontations in the theoretical plane like Figure 8 and in the observed plane with cluster sequences, one should gain some insight in the accuracy and reliability to which present models have arrived.

Note: the results presented here are expounded and discussed in more details in Pont et al. (1997).

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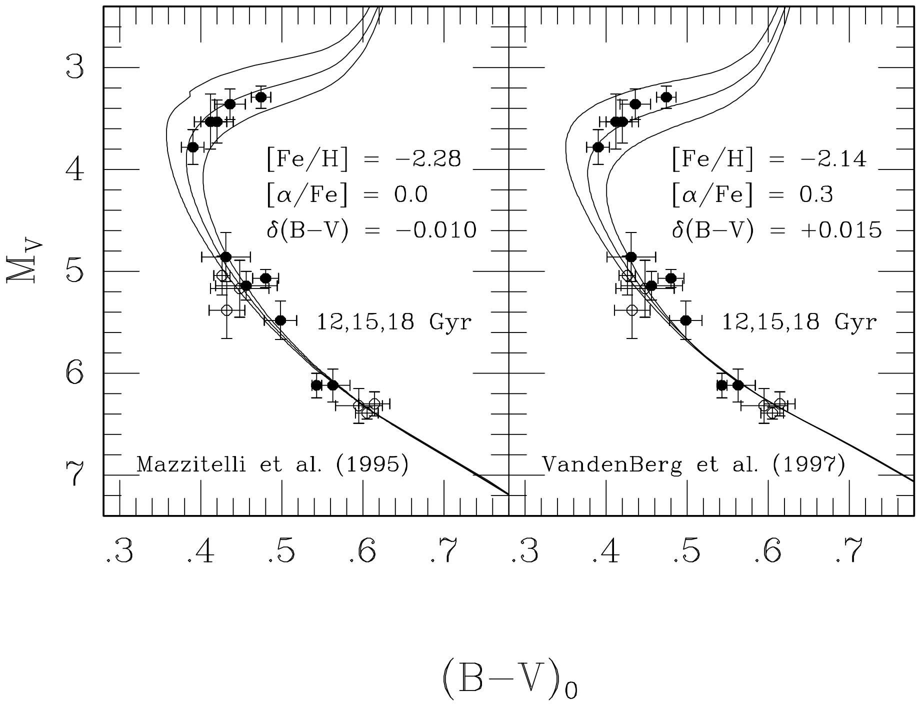

Figure 7. The objects of Table 1 (corrected for biases and binarity) in the HR diagram with Mazzitelli et al. (1995) and VandenBerg et al. (1997) isochrones, for ages of 12, 15 and 18 Gyr.

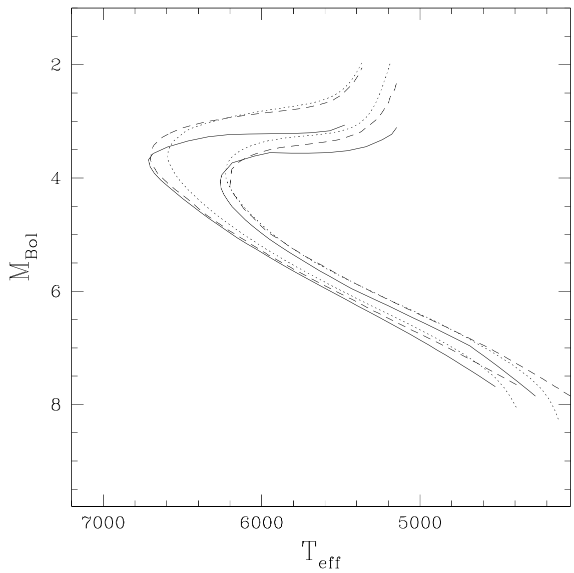

Figure 8. Comparison of three recent sets of isochrones in the theoretical plane, for [Fe/H]= −2.2 and −1.2, and an ages of 12 Gyr (C. Charbonnel: solid line, Y. Lebreton: dashes, Mazzitelli et al.: points). Most differences can be attributed to the temperature predictions, and comparable turnoff luminosity are obtained.

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