Mem. S.A.It. Vol. 77, 1065

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Revisiting the Geneva-Copenhagen Survey ⋆

J. Holmberg[1,2], B. Nordström[3], and J. Andersen[3,4]

[1] Max-Planck-Institut für Astronomie, Königstuhl 17, DE-69117 Heidelberg, Germany
[2] Tuorla Observatory, Väisäläntie 20, FI-21500 Piikkiö, Finland
[3] The Niels Bohr Institute, Astronomy Group, Juliane Maries Vej 30, DK-2100 Copenhagen, Denmark
[4] Nordic Optical Telescope Scientific Association, Apartado 474, ES-38 700 Santa Cruz de La Palma, Spain.

Abstract. Ages and metallicities of stars in the Solar neighbourhood are fundamental constraints on models of the evolution of galactic disks. They are derived from the observations through calibrations which may introduce systematic errors. Understanding and minimising such errors and their interaction with any selection biases in the sample is crucial for the interpretation. We determine substantially improved calibrations of *uvbyβ* photometry into T_{eff} and [Fe/H], evaluate their effects on the computed ages, and perform extensive numerical simulations to verify the robustness of the derived relations. We then revisit the main results of the Geneva-Copenhagen Survey (Nordström et al. 2004), the largest and least-biased complete sample of nearby long-lived stars in the solar neighbourhood, finding the fundamental conclusions to remain unchanged.

Key words. Galaxy: stellar content – Galaxy: solar neighbourhood – Galaxy: disk – Galaxy: evolution – Stars: fundamental parameters

1. Introduction

Models for the evolution of spiral galaxy disks, such as that of the Milky Way, describe their star formation history, nucleosynthesis, chemical enrichment, and dynamical evolution. Traditional models yield single-valued relations for the increase in the (total or individual) heavy-element abundances at a given position in the disk, the radial gradients in metal abundance, and the increase in velocity dispersion of well-defined groups of stars, all as functions of time. The Milky Way is the one galaxy in which these predictions can be tested in detail. Thus, complete, accurate information on the stellar content of the Solar neighbourhood remains a fundamental observational constraint on any set of models. The most comprehensive recent study of nearby stars in the solar neighbourhood is the Geneva-Copenhagen Survey (GCS) (Nordström et al. 2004). The GCS provides metallicities, ages, kinematics, and Galactic orbits for a complete, magnitude-limited, all-sky sample of ∼14,000 F and G dwarfs brighter than $V \sim 8.3$. The basic observational data are *uvbyβ* photometry, Hipparcos/Tycho-2 parallaxes and proper

Send offprint requests to: Johan Holmberg (E-mail: *holmberg@mpia.de*)

⋆ Based in part on observations made with the Danish 0.5-m and 1.5-m telescopes at ESO, La Silla, Chile.

motions, and some 63,000 new, accurate radial velocity observations, supplemented by earlier data. The best calibrations then available were used to derive T_{eff}, [Fe/H], and distances from the photometry, and the astrometry and radial velocities were used to compute space motions and identify binaries in the sample. Finally, unbiased ages and error estimates were computed from a set of theoretical isochrones by a sophisticated Bayesian technique (Jørgensen & Lindegren 2005), and Galactic orbits were computed from the present positions and velocity vectors of the stars and a Galactic potential model. The GCS is large enough to yield adequate statistics for subsets of stars defined by age, metallicity, or abundance, and essentially free of the kinematic and/or metallicity biases affecting most earlier samples. However, systematic selection effects may remain in the data or be introduced by the calibrations used to derive astrophysical parameters from the observations. Accordingly, the purpose of the present paper is to critically re-examine the observational determination of T_{eff}, [Fe/H], and age for F- and G-type dwarf stars in the light of the most recent developments in the field.

2. Temperature calibration

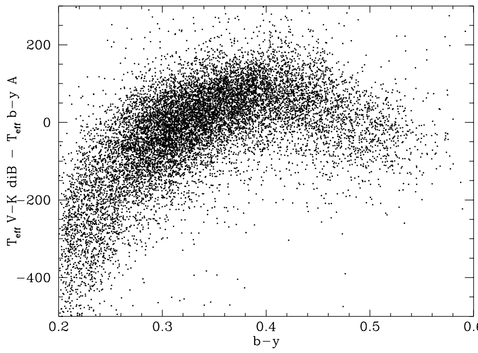


Fig. 1. The difference between T_{eff} from the Alonso et al. (1996) *b-y* calibration, used in the GCS, and T_{eff} as derived from the V-K calibration by di Benedetto (1998).

Temperatures in GCS are based on the Alonso, Arribas & Martínez-Roger (1996) calibration of *b-y*, m_1 and c_1. Alternatively, temperatures based on V-K can be used, because 2MASS photometry is available and well suited to our colour and magnitude ranges. In contrast to calibrations based on only visible colours, T_{eff} estimates based on V-K are remarkably consistent. As an example, the V-K calibrations of Alonso et al. (1996), Ramírez & Meléndez (2005b), and di Benedetto (1998) agree pairwise to within ~20K for the stars in the GCS. In contrast, the Alonso et al. (1996) V-K and *b-y* calibrations differ by 180K rms! We have used the calibration of di Benedetto (1998), which is in excellent agreement with the IRFM temperature scale of Ramírez & Meléndez (2005a) and is valid for the whole colour range of the GCS.

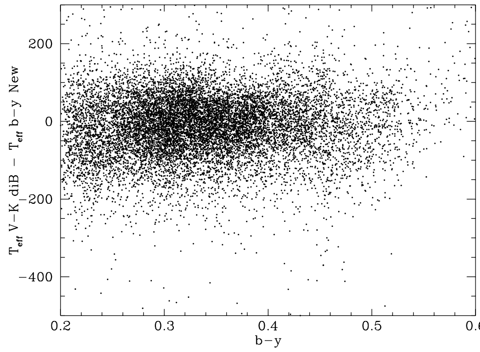


Fig. 2. Differences between the T_{eff} of GCS stars as derived from the new *b-y* calibration and from the V-K calibration by di Benedetto (1998).

Because of the larger number of suitable calibration stars available, the V-K calibration has less systematic error. However, the observational accuracy of the *b-y* index is substantially better than that of V-K. We have therefore derived a new T_{eff} calibration for *b-y*, based on the V-K temperature scale set by di Benedetto (1998). The dispersion of the fit is 60K. We note that this calibration yields 5777K for the Sun when using $(b\text{-}y)_\odot = 0.403$ from Holmberg, Flynn & Portinari (2006), although this was not forced on the fit.

3. Metallicity calibration

The determination of accurate metallicities for F and G stars is one of the strengths of the Strömgren *uvbyβ* system. Among the then available *uvbyβ* calibrations, the GCS used that by Schuster & Nissen (1989) for the majority of the stars. However, this calibration was found to give substantial systematic errors for the very reddest G and K dwarfs ($b-y > 0.46$), where very few spectroscopic calibrators were available at that time. In GCS, we therefore derived a new 'red' relation in the colour range $0.44 \leq b-y \leq 0.59$. Further, about 2400 GCS stars with high $T_{\rm eff}$ and low log g were outside the range covered by the Schuster & Nissen (1989) calibration. For these stars, the calibration of β and m_1 by Edvardsson et al. (1993) was used when valid. For stars outside the limits of both calibrations, we derived a new 'blue' relation in the colour range $0.18 \leq b-y \leq 0.38$.

In order to define an improved photometric metallicity calibration, we select only spectroscopic investigations using a correct temperature scale. This gives a total sample of 573 stars from Edvardsson et al. (1993), Chen et al. (2000), Reddy et al (2003), Allende Prieto et al. (2004), and Feltzing & Gustafsson (1998). They all have a very consistent metallicity scale: Comparing stars in common yields differences of of 0.02 dex or smaller in the mean, with a dispersion of ~0.07 dex.

We derived a new fit of the *uvby* indices to spectroscopic [Fe/H] values from this high accuracy sample. This new calibration is used for stars with $0.30 < b-y < 0.46$, together with the 'blue' and 'red' calibrations derived in GCS.

The consistency of the photometric metallicities from this calibration with the spectroscopic reference values is shown in Fig. 3. The dispersion around the mean is 0.07 dex – the same as between two different spectroscopic measurements. The calibration derived above is also in good accordance with the two relations derived in the GCS. Compared to the 'blue' relation, the mean difference is 0.02 (dispersion 0.04) in the common range of $0.3 < b-y < 0.32$. Compared to the 'red' relation, the mean difference is 0.00 (dispersion 0.09) in the common range of $0.44 < b-y < 0.50$.

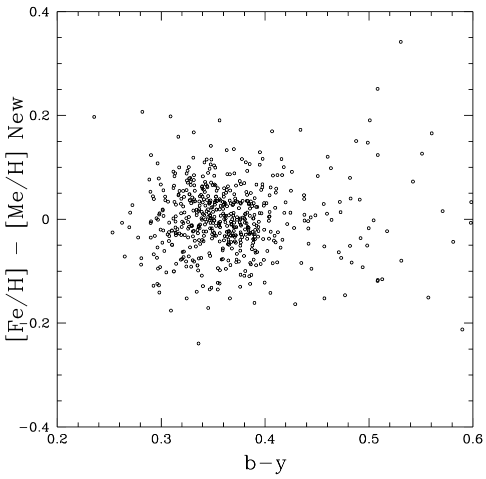


Fig. 3. Modern high accuracy spectroscopic [Fe/H] determinations vs.the new photometric metallicity calibration derived in this paper.

3.1. The Hyades cluster

The Hyades cluster has been used by e.g. Haywood (2005) to assess the zero-point of the GCS metallicity calibration. This leads to misleading conclusions due to the unfortunate fact that the photometry of the cluster stars is not on the same system as the rest of the GCS, as shown by a comparison with the original *uvbyβ* photometry of the cluster by Crawford & Perry (1966).

The result of using Crawford & Perry (1966) photometry combined with the GCS calibrations is shown in Fig. 4. With the GCS calibration, the Hyades then have [Fe/H] = 0.10 ± 0.10. The derived [Fe/H] for the Hyades corresponds well to the standard value, as expected because it is mostly based on the Schuster & Nissen (1989) calibration, which used the Hyades as a main anchor point.

Using the new calibration instead yields [Fe/H] = 0.06 ± 0.07. A different photometric [Fe/H] for the Hyades is to be expected, considering the non-standard He/Fe ratio of this cluster (Clem et al. 2004). The dispersion among the cluster stars is no larger than in the field star calibration, but there is an offset of about 0.07dex. This means that it is neither advisable to include the Hyades in a general calibration of photometric metallicities, nor when comparing different metallicity scales.

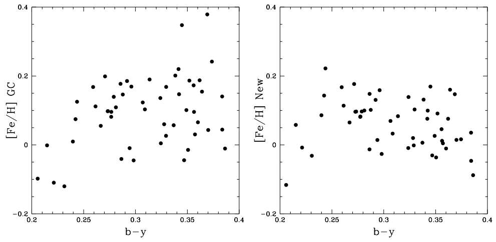


Fig. 4. *Left:* The GCS metallicity calibration applied to the Crawford & Perry (1966) *uvbyβ* photometry of the Hyades. *Right:* Using the new calibration instead.

4. Stellar ages

In the GCS, great effort was devoted to the derivation of ages and masses and their uncertainties for the stars of the survey, using the Bayesian computational technique of Jørgensen & Lindegren (2005) and verifying the correspondence between the computed and observed lower main sequences. Using the new temperature and metallicity calibrations, the temperature corrections applied to the isochrones in the GCS need slight revision.

Wide physical binaries as confirmed by proper motions and radial velocities provide another check of the accuracy of our metallicity and age determinations. We have selected 18 such pairs from the GCS, with separate measurements of all parameters and no indication of further multiplicity. The pairs have a wide distribution in [Fe/H], from -0.4 to +0.1, and ages in the range 0–10 Gyrs.

With the GCS calibrations, the rms difference in [Fe/H] between the two components is 0.11dex; using the new calibrations reduces it to 0.06 dex, in excellent agreement with our other error estimates. The accuracy of the age determination can be estimated from the ratio of the age difference, ΔAge, and the combined 1σ age uncertainty, σAge. For the GCS ages $\Delta Age/\sigma Age$= 0.87, which is reduced to 0.67 with the new calibrations. If this is distributed between the lower error in [Fe/H] (0.07 dex) and that in $T_{\rm eff}$, the latter is about 0.005 dex, again as expected for the new temperature determination.

Fig. 5 compares the GCS ages, computed with the old [Fe/H] and $T_{\rm eff}$ calibrations, with the ages computed using the new calibrations from this paper. Overall, the differences are insignificant, much smaller than the estimated individual uncertainties. On average, the largest ages decrease by ∼10%, which has negligible impact on the interpretation.

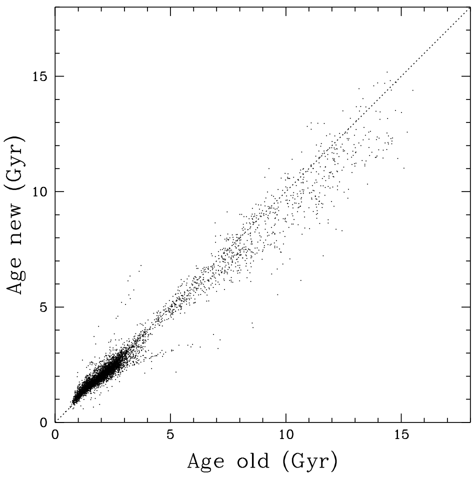


Fig. 5. Ages based on the new metallicity and temperature calibrations vs. those in the GCS, using only single stars with ages better than 25% in both sets. The dotted line shows the 1:1 relation.

The only noteworthy deviations occur on the two "branches" that can be seen in Fig. 5. This small group of stars is located in the "hook" region in the HR diagram, where an observed point is matched by two different isochrones, one placing the star on the main sequence turnoff, the other on the early subgiant branch. As explained e.g. in Jørgensen & Lindegren (2005), this leads to a two-peaked G-function structure, and small changes in the assumed [Fe/H] and T_{eff} may change the relative heights of the peak and thus the most probable age of the star. One could introduce a weighted mean value rather than just a fit to the maximum of such double-peaked G-functions, but the improvement would be primarily cosmetic.

5. Discussion: Evolution of the Milky Way disk

Based on the new calibrations and model corrections discussed above, we have computed new [Fe/H], T_{eff}, ages, and age uncertainties for all the stars in the GCS. In the following, we discuss the implications of the new data for our understanding of the evolution of the Milky Way disk.

In such discussions, it is crucial to not only employ the best possible calibrations from observed to astrophysical parameters, but also to understand to what extent the criteria used to select the current sample of stars may influence the conclusions drawn. This is especially important when studying subsamples selected on the basis of having one or more of the derived parameters available, perhaps within a certain level of precision, rather than the entire GCS. To estimate the interplay between the sample selection criteria and any errors in the determination of the derived parameters in the GCS, we constructed a simulated catalogue. The basic stellar sample consists of a mix of three populations, i.e. thin disk, thick disk and halo, with separate distributions in metallicity, kinematics and SFR, but all with the same IMF in the range 0.75-2.5 $M_{\odot}$. The combined catalogue, like the GCS, contains about 15000 stars with 90% disk, 8% thick disk and 2% halo stars, and the distribution of stellar parameters and measurement errors is also like the real catalogue. By applying the various calibrations, computations, and parameter cuts to the simulated catalogue as well as to the observed sample, we can ascertain in quantitative term which systematic effects are introduced at each stage and whether they have any decisive influence on the conclusions.

5.1. The age-metallicity diagram

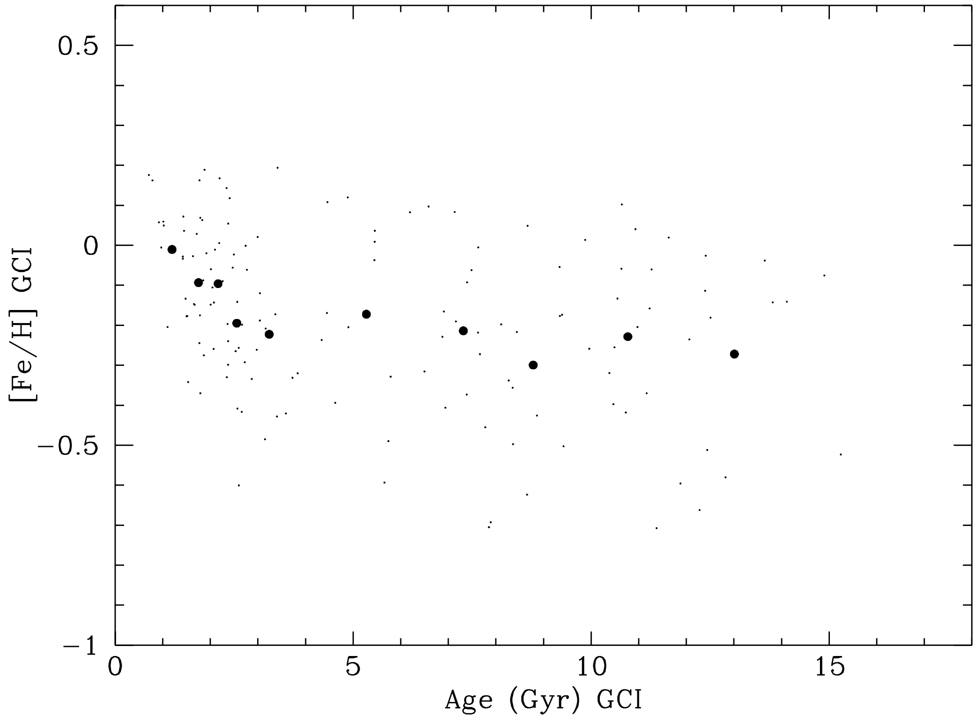
The relationship between average age and metallicity for stars in the solar neighbourhood – the so-called age-metallicity relation – (AMR) is probably the most popular diagnostic diagram for comparing galactic evolution models with the real Milky May. There is, however, no consensus on its interpretation.

The discussion centres essentially on the existence or otherwise of a general slope of the AMR, i.e. a gradual increase in [Fe/H] with time, and whether the scatter in [Fe/H] at any given age is of observational origin or reflects a greater complexity in the evolution of a real galaxy than accounted for by the models. It is thus crucial to ascertain whether the distribution of stars in the age-metallicity diagram (AMD) reflects intrinsic properties of the sample or just artefacts of the measurement and parameter calculation procedures.

This can be investigated by means of our simulated sample. First, we see whether the new calibrations have by themselves caused any significant change in the AMD, using the stars with the very best ages ($\sigma(Age)$ <25% and d <40pc; Fig. 6). As seen, the revised calibrations cause hardly any difference in the AMD.

Perhaps the most obvious structure in the observed AMD is the marked increase in mean metallicity and the absence of metal-poor stars for ages below 2 Gyr (see Fig. 6 and GCS Figs. 27-28). It is important to understand if this is due, at least in part, to the selection criteria used to define the catalogue sample, or whether it is a genuine property of the solar neighbourhood. In the latter case, it could be interpreted as a cut-off in the resupply of fresh low-metallicity gas, followed by closed-box evolution.

Fig. 7 (lower left panel) shows that a simulated sample with a flat input AMR for the thin disk shows the same deficiency of young



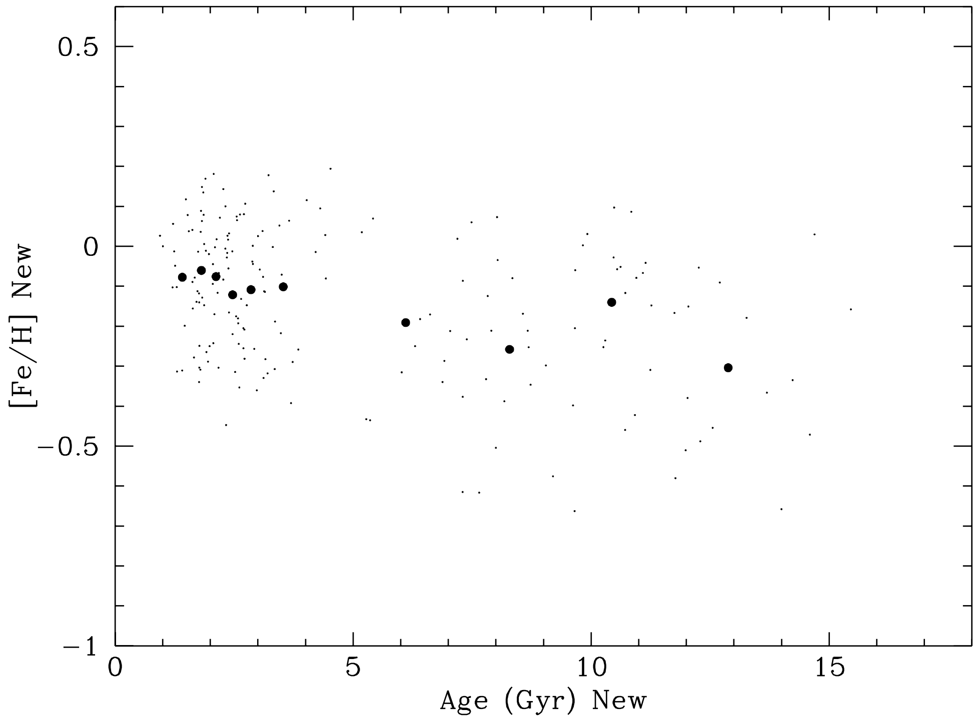


Fig. 6. *Top:* AMR from the original GCS, for single stars with ages better than 25% and $d <$ 40 pc. Large dots are mean values in bins with equal numbers of stars. *Bottom:* Same, using the improved stellar parameters.

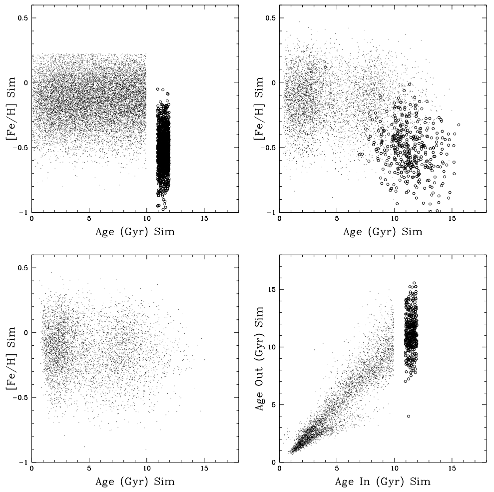


Fig. 7. AMR computations for the simulated sample. *Top left:* The input AMR, flat within each of the thin and thick disks. *Top right:* The "observed" AMD for the simulated sample, using the synthetic observations with the new calibrations and restricting the figure to stars with ages better than 25%. Thick-disk stars are shown as open circles. *Bottom left:* AMD for the thin-disk stars only, imposing a blue colour cutoff at b-$y \leq 0.205$ as in the GCS. *Bottom right:* Derived ages vs. the "true" input values.

metal-poor stars in the observed diagram (especially those using the new calibrations), indicating that the effect is caused by the blue colour cutoff at b-$y \leq 0.205$ used to define the GCS sample.

In order to verify whether our calibrations or age computations could introduce (or remove) trends at higher ages in the AMD, we imposed tight AMRs (width 0.1 dex at all ages) on a subset of the simulated catalogue. In order to test our computations for stars with all combinations of age and metallicity, we assumed both a linear increase in [Fe/H] with time as well as a similar, fictitious (and completely unphysical!) linear *de*crease of [Fe/H] with time.

Fig. 8 compares the input and recovered AMD for both of these cases. As can be seen, the slope of the input AMR is faithfully reproduced in both cases despite the inevitable scatter introduced by the observational errors.

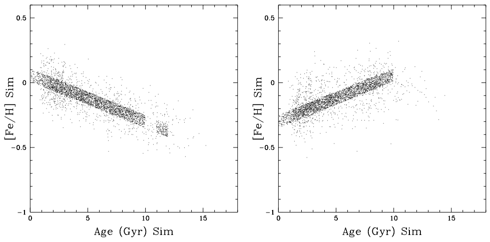


Fig. 8. Input and "observed" AMR for the simulated catalogue, in Fig. 7. *Left:* With an input AMR restricted to a 0.10 dex wide band of slope -0.036 dex/Gyr. *Right:* Same, but assuming an (unphysical) slope of +0.036 dex/Gyr.

6. Conclusions

Our review of the basic calibrations used to determine astrophysical parameters for the stars in the GCS from *uvby* photometry has resulted in substantially improved temperatures for especially the hotter stars, minor corrections to [Fe/H], and substantial improvement in the absolute magnitude (i.e. distance) determinations. These results are obtained by drawing on the large body of 2MASS K photometry and high-resolution spectroscopic abundance analyses now available.

Using the improved astrophysical parameters, we have recomputed the ages and age error estimates for the GCS sample, and also recomputed the temperature corrections needed for the models to agree with the unevolved main sequence at metallicities below solar. The resulting ages are in good agreement with those published in the GCS.

We note that, because of a problem with the *uvby* photometry for the Hyades stars and the non-standard He abundance of this cluster, the Hyades cannot be used to check the metallicity or age scales for field stars.

The new [Fe/H] values change the observed metallicity distribution only marginally; it is still in strong disagreement with the prediction of closed-box galactic evolution models.

In preparation for the discussion of Galactic relations involving stellar ages, notably the age-metallicity diagram, we have performed extensive simulations of the effects of our selection and computation procedures by applying them to a synthetic catalogues with properties closely resembling those of the GCS, but with specified intrinsic properties such as the AMR. We find that our methods faithfully recover the 'true' relations within the observational errors, and without introducing systematic effects.

The observed AMR retains the general features of that of the GCS, i.e. little or no variation in mean metallicity with age in the thin disk, plus an admixture of perhaps 3% thick-disk stars, and with a large and real scatter in [Fe/H] at all ages.

Acknowledgements. We reiterate our grateful thanks to our many collaborators on the original GCS project from Observatoire de Genève, the Harvard-Smithsonian Center for Astrophysics, ESO, Observatoire de Marseille, and our own institutes. The GCS was made possible by large amounts of observing time and travel support from ESO, through the Danish Board for Astronomical Research, and by the Fonds National Suisse pour la Recherche Scientifique. We also gratefully acknowledge the substantial financial support from the Carlsberg Foundation, the Danish Natural Science Research Council, the Smithsonian Institution, the Swedish Research Council, the Nordic Academy for Advanced Study, and the Nordic Optical Telescope Scientific Association. This publication makes use of data products from the Two Micron All Sky Survey, which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by the National Aeronautics and Space Administration and the National Science Foundation. We have also made use of the SIMBAD and VizieR databases, operated at CDS, Strasbourg, France.

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