TRACING THE ORIGIN OF THE SOLAR NEIGHBOURHOOD

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ABSTRACT

The *Geneva-Copenhagen Survey of the Solar Neighbourhood* provides accurate age, metallicity, kinematic, and duplicity information for a complete, unbiased, magnitude-limited sample of ∼14 000 nearby F and G dwarfs, volume limited to ∼40 pc. The results challenge traditional models of the evolution of the disc. We discuss the basis for these conclusions and outline the improvements needed to make further progress on the subject, especially as regards the determination of stellar ages and Galactic orbits.

Key words: Milky Way; Galactic disc; Solar neighbourhood; stellar kinematics; radial velocities.

1. THE SURVEY

The *Geneva-Copenhagen Survey of the Solar Neighbourhood* (Nordström et al. 2004) has provided precise, multi-epoch radial-velocity observations for ∼14 000 nearby F and G dwarfs, selected from the all-sky $uvby\beta$ photometry by Olsen (1994) and earlier papers. New calibrations and computations were used to complete the age, metallicity, kinematics, and duplicity information for this magnitude-limited sample of long-lived stars, which is complete, unbiased, and volume complete to ∼40 pc. For details of the methods employed and results obtained, see Nordström et al. (2004).

When used to re-derive the standard diagnostic relations for models of the chemical and dynamical evolution of the disc, our results show that traditional analytic models fail all the classical tests: Describing just the time evolution of mean properties such as average metallicity or kinematics completely misses the true complexity of the physics at work, and a qualitatively new generation of models is needed.

Given the far-ranging implications of this conclusion, we review its observational basis and suggest useful directions for future work in the context of the Gaia mission.

2. RELIABILITY OF THE BASIC DATA

In this section we briefly summarise the techniques and tests we have developed to ensure that results derived from our observations are not distorted by larger random and/or systematic errors than stated in the paper.

2.1. Metallicities

Our metallicity values are derived from the Strömgren $uvby\beta$ indices, using the calibration by Schuster & Nissen (1989) within its range of validity. High-resolution spectroscopic [Fe/H] values from Edvardsson et al. (1993) and more recent papers were used to check the accuracy of the calibration and extend it towards hotter and cooler stars. The resulting [M/H] values are found to be accurate to within 0.10 dex. Given the large number and diverse sources of the spectroscopic results, it is very unlikely that calibration errors as large as 0.05 dex remain in our sample in any range of colour or [Fe/H].

2.2. Ages

Good age information is, of course, crucial when investigating the evolution of any astrophysical object, such as the Galactic disc. Because chromospheric emission essentially vanishes at about the age of the Sun, ages for our stars must be derived by comparison with theoretical isochrones. Isochrone ages and – especially – their uncertainties are, however, notoriously difficult to compute for old, low-mass stars, and we have devoted a great deal of effort to this task. Note that most of the binary stars in the sample are known and can be removed as necessary.

The main input parameters and sources of error in the age computations are:

- *Metal abundance.* Z (or [Fe/H]) is needed to interpolate in isochrones computed for different metallicities. The accuracy of our [M/H] values is discussed above. The observed average enhancement of the

α-elements in metal-poor stars (e.g., Edvardsson et al. 1993) has been included in the computation of Z for each value of [M/H]. The α-enhancement may be somewhat different for thin- and thick-disc stars (e.g., Fuhrmann 1998), but there is insufficient information to apply more detailed corrections unless individual element abundances are available, as e.g., in Edvardsson et al. (1993).

- M_v. A check using the best Hipparcos parallaxes ($\sigma < 3\%$) shows that our photometric distance estimates for single stars are accurate to $\pm 13\%$, so our M_v values are accurate to 0.26 mag or better.
- *Temperature*. $T_{\rm eff}$ is the most direct indicator of age for stars that have evolved above the ZAMS in the HR diagram. Given our earlier experience with the different temperature-colour relations of various stellar models (Nordström et al. 1997), we have computed $T_{\rm eff}$ for the survey stars from the $uvby\beta$ indices and the Alonso et al. (1996) calibrations, which are based on the IR flux method.

  The observed $T_{\rm eff}$ were compared directly with the model predictions for different values of [Fe/H] (Girardi et al. 2000; Salasnich et al. 2000). It was found that the unevolved main sequence ($M_v >$ 5.5) matched the observed stars only at Solar metallicity and for [Fe/H] < -2, but was significantly hotter at intermediate metallicities. Accordingly, a metallicity-dependent temperature correction was applied to the isochrones before using them to derive ages. Note that any constant correction – including none – would have led to a spurious correlation between age and metallicity.
- *Computation*. The traditional technique to determine isochrone ages is to plot the observed point in the HR diagram and assign the age of the interpolated isochrone passing through that point to the star under consideration. Errors are estimated by successively varying the input parameters by $\pm 1\sigma$, noting the change in age, and adopting an average value as the error of the age.

  For the survey, we have developed a far more sophisticated and robust technique. Briefly, for every point in the 'HR cube' ($T_{\rm eff}$, M_v, Z) we compute the probability that the observed point could in reality fall there, given the known (Gaussian) observational errors, and the star thus has the age of the isochrone passing through that point. These probabilities are then integrated over all values of the stellar mass to form the *a posteriori* probability density function (or 'G function') for all possible values of the age.

  In the process, we account for the *a priori* distribution of stellar masses in a fully Bayesian manner, but do not impose any preconceived ideas on the *a priori* distribution of metallicities or ages in the sample. Tests have shown that lower and upper 1σ error limits are defined by the age values where the G function drops to 60% of its maximum value. If both of these fall within the range of ages covered by the isochrones (here 0–17.8 Gyr), we call the age 'well-defined'; otherwise only upper or lower bounds on the age are provided.

Our procedures are described by Nordström et al. (2004) and in more detail by Jørgensen & Lindegren (2004); they are conceptually similar to that proposed by Pont & Eyer (2004), but differ significantly in the α-element enhancement and in the choice of metallicity calibration and temperature corrections to the models, all of which are of key astrophysical importance. Both approaches represent significant improvements in the treatment of statistical biases and realistic error assessment relative to the classical technique.

Note that even 'well-defined' ages may have large errors, but at least those errors are reliably known. Note also that crowding of the isochrones prevents the computation of 'well-defined' ages for stars in large parts of the HR diagram, including the very youngest and oldest stars: The stars with good ages are *not* a representative subset of the full sample!

2.3. Space Motions

Our radial velocities are of superior quality, with a typical mean error of 0.25 km s^{-1} for a velocity based on $\sim$4 observations over a few years. This allows us to detect 3223 spectroscopic binaries, a significant fraction of the 5622 (34%) binary stars of all types in the sample.

The Tycho-2 proper motions contribute only $\sim 0.7\,{\rm km\,s^{-1}}$ to the error of the space motions, which is dominated by the parallax/distance uncertainties. Overall, our space motions are accurate to $\sim 1.5\,{\rm km\,s^{-1}}$ in each of *U, V*, and *W*. This implies that the stars can be meaningfully followed backward or forward in their Galactic orbits for about two full orbital cycles, provided the Gravitational potential is correspondingly well known.

3. FIRST RESULTS FROM THE SURVEY

We have used the new data set to revisit a number of the classical diagnostic relations for the evolution of the Galactic disc.

3.1. The G Dwarf Problem

The term 'G dwarf problem' refers to the observed lack of the metal-poor low-mass stars that should have survived from the early generation whose massive members produced the heavy elements we see in today's Population I stars (van den Bergh 1962). If real, it implies that external processes were important, such as pre-enrichment or infall of metal-poor gas, but a low-velocity metal-poor population might also have been missed in earlier, proper-motion based, incomplete surveys.

The definitive discussion of the metallicity distribution of the local long-lived stars by Jørgensen (2000), based on our survey, showed that the previously unobserved stars are, in fact, predominantly metal *rich*. The solution to the

G dwarf problem is to be sought in the models, not in the observations.

3.2. The ‘Age-Metallicity Relation’ (AMR)

Since the pioneering work by Twarog (1980), the shape of the gradual rise in mean metallicity with time has been used to constrain models of Galactic chemical evolution and nucleosynthesis. The age-metallicity diagram defined by our single stars within 40 pc and with well-defined ages is shown in Figure 1.

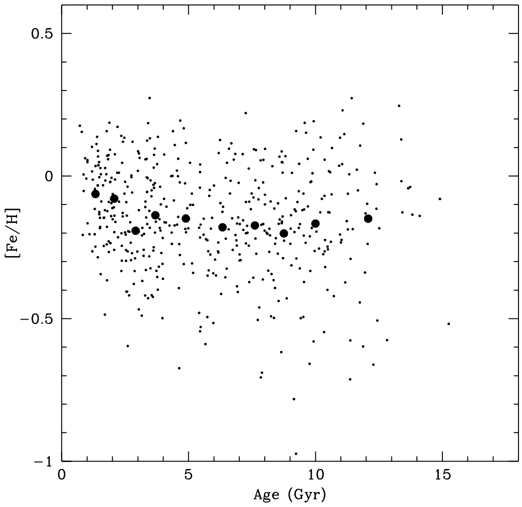

Figure 1. Age-metallicity diagram for the 462 single stars within 40 pc and with well-defined ages. Large dots indicate mean values in bins with equal numbers of stars.

Figure 1 shows a striking lack of overall change of the mean metallicity with time (see also, e.g., Feltzing et al. 2001) as well as a scatter at all ages which is much larger than the observational uncertainty. Note that the scatter is essentially identical to that found by Edvardsson et al. (1993) from high-quality spectroscopy; however, the downward trend of their AMR at large ages was, as they point out, caused by their red colour cutoff, which by definition excluded the old metal-rich G and early K dwarfs which are included in our survey. Note also that a failure to apply appropriate temperature corrections to the models would have produced spuriously high ages for the metal-poor stars and an AMR of conventional shape.

That old, metal-rich stars do exist in the disc seems still to be controversial, but was known already to Strömgren (1963). It is further substantiated by such old, metal-rich star clusters as NGC 6791 (Sandage 2003). We are confident that the main features of Figure 1 are not materially distorted by errors in our metallicities and/or ages.

The consequences of the shape of the ‘relation’ in Figure 1 are major, however: If the dispersion in [Fe/H] at all ages is much larger than the change in mean metallicity over 10 Gyr, the chemical evolution of the disc must have proceeded at very different speeds at different locations in the disc – even at the same galactocentric radius – or a major reshuffling of stars between enrichment sites has taken place. Note that the production *ratios* between different elements seem to have remained constant throughout this process (Edvardsson et al. 1993). Chemical evolution models giving only single-valued predictions for the run of metallicity vs. time would appear to miss crucial parts of the real physical picture.

3.3. The Age-Velocity Relation

Our sample also enables us to derive the change of the stellar velocity dispersion with time. We find a continuous rise throughout the age of the disc, contradicting the saturation after 2 Gyr proposed by Quillen & Garnett (2001) – implying that kinematic traces of any early mergers are now erased in the disc – but insufficient to explain the scatter in the AMR by migration of stellar orbits as proposed by Wielen et al. (1996). The slope of the relation does not match any of the traditional disc heating candidates, but seems consistent with the heating by transient spiral arms discussed by De Simone et al. (2004).

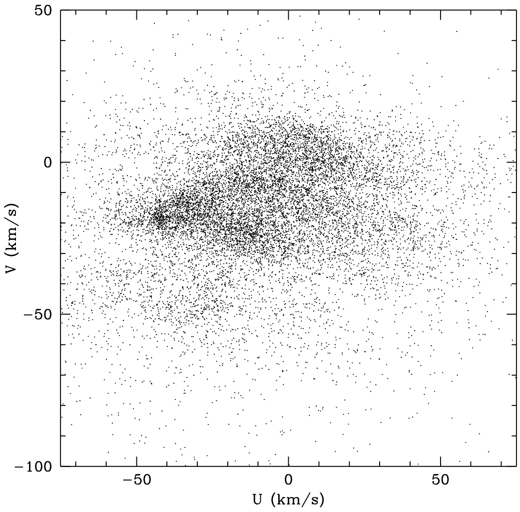

Figure 2. U-V diagram for all single stars with complete kinematical data in the sample.

3.4. Characteristics of Stellar Populations and the Galactic Potential

The *U-V* velocity diagram for all single stars in our survey is shown in Figure 2. The strong banded structure is similar to that seen by Dehnen (1998) and Skuljan et al. (1999), but definitely not a superposition of Gaussian velocity distributions corresponding to the thin and thick discs. This would appear to call into question the standard kinematic criteria for assigning local stars to these two populations (Fuhrmann 1998; Feltzing et al. 2003).

Moreover, as the features in Figure 2 display wide ranges in [Fe/H] and age, they are not similar to classical moving groups, but indicate significant non-smoothness of the Galactic disc potential, as pointed out by Famaey et al. (2004). Calculating stellar orbits back in time for more than half an orbital revolution appears a dubious procedure if a smooth, axisymmetric potential is assumed – as we have done when computing orbital parameters for the stars in our survey.

4. PROGRESS IN THE GAIA ERA

For progress in our understanding of the chemical and dynamical evolution of the Milky Way disc, the relations between metal abundance and age clearly need to be defined with better accuracy and in more detail. More detailed individual element abundances for key subsets of stars would help, but the greatest need for improvement is in the ages. With proper computational methods now essentially established, the greatest remaining source of uncertainty is the effective temperature scales for the stars as well as the models. Empirical temperature calibrations as well as model boundary conditions need urgent improvement - with consistent results! – before much further progress can be expected.

Along with better temperatures and metallicities, the more accurate parallaxes from Gaia would certainly contribute to better age determinations in larger regions of the HR diagram. However, as the observational accuracy improves, so must that of the models and the transformations to observational quantities for better ages to result, especially for the youngest and oldest stars. Similarly, although better space motions are always welcome, the main obstacle to computing more reliable Galactic orbits for the nearby stars is already now our incomplete knowledge of the gravitational potential in which they move, not the observed space motions themselves.

We conclude that the most urgent need for progress in understanding our own neighbourhood is not more accurate parallaxes or motions for many more stars, but progress in understanding the underlying physics of stellar and galactic structure. These problems can be addressed from existing stellar samples, such as ours, and need to be resolved before the full potential of the Gaia mission can be realised.

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