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The Geneva–Copenhagen Survey of the Solar Neighbourhood

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Abstract: We report on a new survey of metallicities, ages, and Galactic orbits for a complete, magnitude-limited, and kinematically unbiased all-sky sample of 16 682 nearby F- and G-dwarfs. Our ∼ 63 000 new, accurate radial velocities for nearly 13 500 of the stars, combined with *Hipparcos* parallaxes and Tycho-2 proper motions, complete the kinematic data for 14 139 stars and allow us to identify most of the binary stars in the sample. Isochrone ages have been determined whenever reliable results are possible, with particular attention to realistic error estimates.

Among the basic properties of the Galactic disk that can be reinvestigated from our data are the metallicity distribution of G-dwarfs and the age–metallicity and age–velocity relations of the solar neighbourhood. We confirm the lack of metal-poor G-dwarfs relative to classical model predictions (the 'G-dwarf problem'), the near-constancy of the mean metallicity since the formation of the thin disk, and the appearance of the kinematic signature of the thick disk ∼10 Gyr ago.

Keywords: Galaxy: solar neighbourhood — Galaxy: disk — Galaxy: kinematics and dynamics — Galaxy: evolution

1 Motivation

The solar neighbourhood affords the most basic tests of models of the Galactic disk: the sample volume around the Sun provides a first estimate of the stellar mass density of the disk in the Galactic plane. The distribution in age of these stars is our record of the star formation history of the disk. Similarly, their chemical abundances as functions of age are the fossil record of the chemical enrichment history of the disk. Finally, the space motions and Galactic orbits of the stars as functions of age are clues to the parallel dynamical evolution of the Galaxy and diagnostics of its mix of stellar populations from different regions of the disk (see, for example, the recent review by Freeman & Bland-Hawthorn 2002).

F- and G-type dwarf stars are excellent tracers of this history. They are both numerous and sufficiently long-lived to survive from the time of formation of the disk; their convective atmospheres reflect their initial chemical composition; and ages can be estimated for at least the more evolved stars by comparison with stellar evolution models. Photometry in the Strömgren $uvby\beta$ system is an efficient means to derive intrinsic stellar properties from observation (Strömgren 1963, 1987). Recent Galactic studies based mainly on $uvby\beta$ photometry are, for example, Jørgensen (2000), Feltzing et al. (2001), and Holmberg (2001).

Our key new contribution consists of accurate, multiple radial velocity observations for an all-sky, magnitude-limited, and kinematically unbiased sample of over 14 000 nearby F- and G-stars. Because this data set is unlikely to be superseded until the results of the *Gaia* mission (Perryman et al. 2001) and/or the RAVE program (Steinmetz 2003) appear, we have also redetermined $T_{\rm eff}$, M_v, and [Fe/H] as well as ages and Galactic orbits for all stars in the sample with adequate data. The program was briefly outlined at an earlier meeting in this series (Nordström et al. 1996); the complete catalogue with a full discussion will appear elsewhere (Nordström et al. 2004).

The much-cited paper by Edvardsson et al. (1993) studied the detailed chemistry of a subset of the sample discussed here. That paper shed much new light on the detailed nucleosynthesis history of the disk, but suffered from strong selection effects which our sample was designed to overcome. Thus, the two studies address the same subject from complementary angles.

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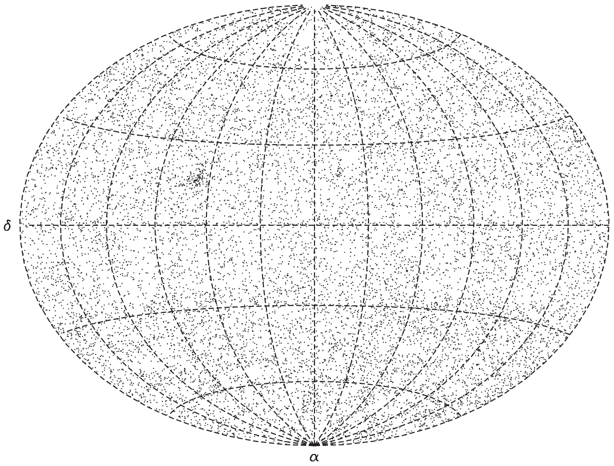

Figure 1 Distribution on the sky of the 14 139 stars with complete kinematical data.

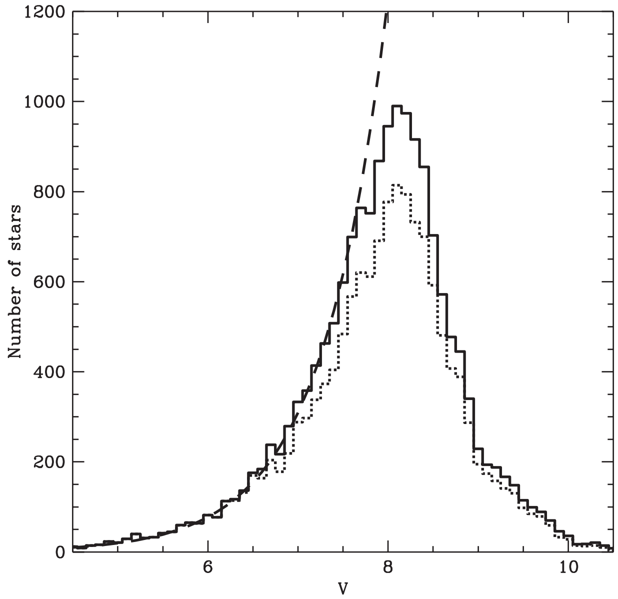

Figure 2 Distribution in apparent magnitude for the full sample (full line), and for stars with radial velocity data (dotted line). The dashed curve shows the relation for a uniform, volume-complete sample.

2 Sample Definition

The stars were selected from the $uvby\beta$ catalogues by Olsen (1983, 1993, 1994a, 1994b) to form a magnitude-limited, kinematically unbiased, all-sky sample of F- and G-dwarfs which would at the same time be volume-complete to a distance of ~40 pc. For details of the selection procedures see Nordström et al. (2004)

The distribution on the sky of the sample stars with complete kinematical data is shown in Figure 1, in equatorial coordinates and in an equi-area projection. Note the concentration of stars in the Hyades — observed with special care for calibration purposes — and the addition of the latest-type dwarfs (to K2 V) south of $\delta = -26°$. Apart from these features, the sample is very uniformly distributed.

The distributions in (apparent) V magnitude for the whole sample and for those stars with complete chemical and kinematical data are shown in Figure 2. The magnitude completeness of the sample can be estimated by comparison with the distribution expected for a uniform volume density of stars. The full sample starts to become incomplete near $V = 7.6$.

3 Observational Data

This section summarises the observational data used to compute the astrophysical and kinematical parameters for our program stars. Our new radial velocity observations are described in detail; the Strömgren $uvby\beta$ photometry is from the catalogues by Olsen (1983, 1993, 1994a, 1994b). For other data, the relevant sources are given below.

3.1 Radial Velocities

Most of the new radial velocity data were obtained with the CORAVEL photoelectric cross-correlation spectrometers (Baranne et al. 1979; Mayor 1985), operated at the Swiss 1-m telescope at Observatoire de Haute-Provence, France, and the Danish 1.5-m telescope at ESO, La Silla. The two CORAVELs thus cover the entire sky, and their fixed, late-type cross-correlation templates efficiently match the spectra of the large majority of our program stars.

Two or more observations have been made for almost all stars over a substantial time base, typically 500–1000 days, but occasionally more than a decade. This allows us to define more reliable mean velocities and identify most of the spectroscopic binaries which, if unrecognised, yield misleading astrophysical parameters from the observed magnitudes and colour indices. Between the two telescopes, a total of 62 993 CORAVEL observations have been made of 12 941 of the program stars discussed in this paper. Additional observations of fast-rotating stars were made at the Center for Astrophysics (Nordström et al. 1997).

The mean radial velocities are very accurate; the distribution of their mean errors is shown in Figure 3. As will be seen, mean errors are typically ~0.25 km s^{-1} and only rarely exceed 1 km s^{-1}. Stars are labelled as binaries when their velocity is variable at the 99% confidence level.

3.2 Parallaxes

Good distances are crucial in order to compute accurate absolute magnitudes, distances, and space motions for the program stars. *Hipparcos* parallaxes, generally of very good accuracy, are available for the majority of these relatively nearby stars (ESA 1997).

3.3 Proper Motions

Accurate proper motions are available for the most of the stars from the Tycho-2 catalogue (Høg et al. 2000). This catalogue is constructed by combining the star-mapper measurements of *Hipparcos* with the Astrographic Catalogue, based on measurements in the Carte du Ciel and

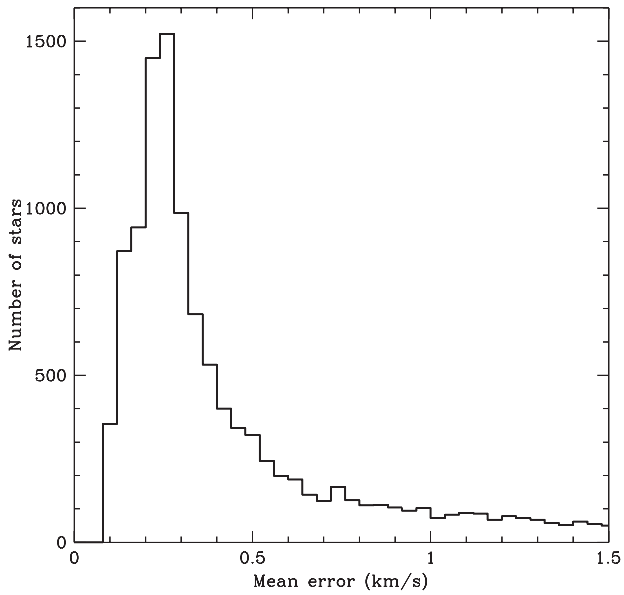

Figure 3 The distribution of the mean errors of the mean radial velocities in the catalogue.

other ground-based catalogues and extending the time base to nearly a century. The mean propagated error in space motion from proper-motion errors alone is only 0.7 km s^{-1}.

4 Derived Astrophysical Parameters

The astrophysical data needed to discuss the evolutionary history of the solar neighbourhood are derived from the observations using the calibrations discussed below.

4.1 Metal Abundances

The accurate determination of metallicities for F- and G-dwarfs is one of the strengths of the Strömgren *uvbyβ* system. Among the available calibrations, we have used that by Schuster & Nissen (1989) for the majority of the stars. Approximately 600 stars in our sample are covered by both the F- and G-star calibrations of Schuster & Nissen (1989), and the mean difference in [Fe/H] is 0.06 dex with a dispersion around the mean of only 0.07. We have further compared these photometric metallicities with the homogeneous spectroscopic values for F- and G-stars by Edvardsson et al. (1993) and Chen et al. (2000). The agreement is excellent, with mean differences of only 0.02 and 0.00 dex and dispersions around the mean of 0.08 and 0.11, respectively. An improved calibration has been derived for stars outside the range of validity of the relations by Schuster & Nissen (1989).

5 Effective Temperatures

Effective temperatures for all stars have been determined from the reddening-corrected *uvby* indices, using the calibration of Alonso et al. (1996) which is based on the infrared flux method. Tests show these temperatures to be accurate to about ±100 K.

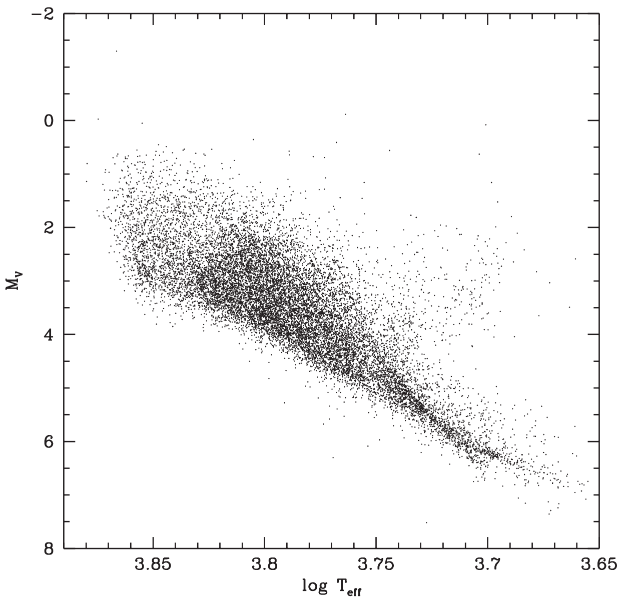

Figure 4 M_V versus log $T_{\rm eff}$ for all stars.

5.1 Distances and Absolute Magnitudes

As most of our program stars have excellent trigonometric parallaxes from *Hipparcos*, we have primarily determined their distances from these parallaxes. The distances are used to compute the tangential space motion components from the proper motions, and the absolute magnitudes used in the determination of ages and masses.

From the best *Hipparcos* parallaxes we find that the photometric distance determinations are accurate to ~13%. Accordingly, we use the *Hipparcos* distance if the parallax is available and accurate to 13% or better; otherwise we adopt the photometric distance, correcting for interstellar extinction when known. A typical error in M_V for our dwarf stars is therefore 0.26 magnitudes or better. The resulting HR diagram is shown in Figure 4.

5.2 Ages

Individual stellar ages are crucial in order to place the observed chemical and kinematical properties of the stars in an evolutionary context. Because of their importance, we have devoted a great deal of effort to determining the ages, and in particular their errors, with far greater sophistication than, for example, Edvardsson et al. (1993), taking both calibration errors and a range of statistical biases into account. The details are beyond the scope of this paper, but are given in Nordström et al. (2004) and Jørgensen & Lindegren (in preparation); at the time of writing, these computations are still in progress.

5.3 Space Velocities

Space velocities have been computed for all the stars from their distances, proper motions, and mean radial velocities. The (U, V, W) components are defined in a right-handed Galactic system with U pointing towards the Galactic centre, V in the direction of rotation, and W towards the north Galactic pole. No correction for the solar motion has been

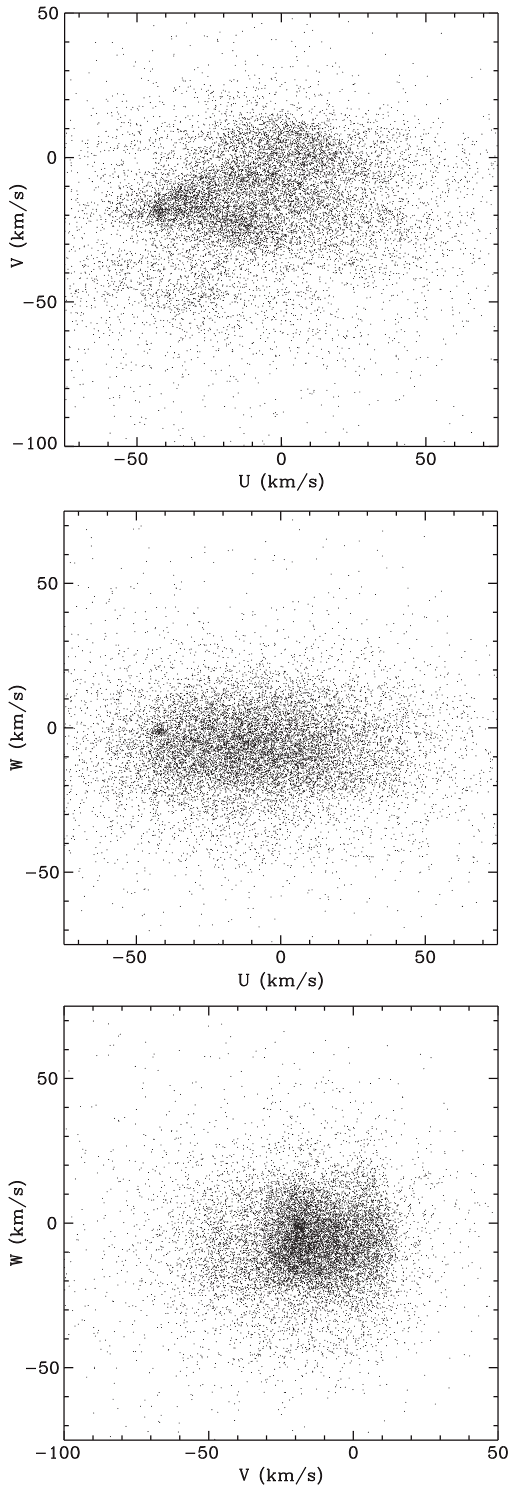

Figure 5 *U–V*, *U–W*, and *V–W* diagrams for all stars in the sample.

made. Figure 5 shows the distributions of all the (*U*, *V*, *W*) velocities in the sample. Average errors in each component are $\sim$1.5 km s^{-1}.

5.4 Galactic Orbits

From the positions and space motion vectors of the program stars we can integrate their orbits back in time and estimate their average orbital parameters. The correlation of such Galactic orbits with the chemical characteristics and ages of the stars may yield valuable new insight; see, for example, Edvardsson et al. (1993).

The observed space motions were corrected for a solar motion of (10.0, 5.2, 7.2) km s^{-1} (Dehnen & Binney 1998). For the orbit integrations we used the potential of Flynn et al. (1996), adopting a solar Galactocentric distance of 8 kpc, a circular rotation speed of 220 km s^{-1}, disk surface density 52 M$_\odot$ pc^{-2}, and disk volume density 0.10 M$_\odot$ pc^{-3} (see Reid et al. 1999; Backer & Sramek 1999; Flynn & Fuchs 1994; Holmberg & Flynn 2000).

6 Discussion

Our new data set allows us to thoroughly re-evaluate many of the global properties of the solar neighbourhood and the Galactic disk. An in-depth analysis will require detailed simulations of the predictions of various competing models, subjecting the simulated stellar populations to the same selection criteria as the observed samples and comparing the results with the real data set. Such simulations will be the subject of future papers, but are beyond the scope of the present short contribution. Here we just illustrate a few of the new insights that can be expected.

The *U–W* and *V–W* diagrams in Figure 5 show a smooth distribution, the Hyades being the only clearly discernible structure. The *U–V* diagram, on the other hand, shows abundant structure in addition to the Hyades, with four curved or tilted bands of stars aligned along approximately constant *V* velocity. These structures have velocities resembling classic moving groups or stellar streams and are usually named (top to bottom): Sirius–UMa, Coma Berenices (or local), Hyades–Pleiades, and Hercules, the latter structure being also known as the *U* anomaly (Dehnen 1998; Skuljan et al. 1999). Because these structures do not consist only of young stars, they cannot be fully described as the resolved remnants of broken-up systems such as classic moving groups, but could be due to kinematic focussing from non-axisymmetric structures of the Galaxy, such as spiral arms or the bar. Our data also allow further searches for dynamical substructure resulting, for example, from past merger events (Helmi et al. 2003).

Among the classical-type analyses, the ‘G-dwarf problem’ has been revisited by Jørgensen (2000), using an early version of the present data. The basic result is that, far from being eliminated by newly discovered, slow-moving, metal-poor stars, the deficit of metal-poor G-dwarfs relative to the predictions of closed-box models is twice as large as before. Obviously, metal-poor stars were in fact over-represented in earlier, kinematically biased samples.

We defer the discussion of the age–metallicity and age–velocity relations until the last details of our age determinations have been settled, as the ages of the very oldest stars depend very sensitively on such details. But our preliminary findings are consistent with those by Feltzing et al. (2001), Edvardsson et al. (1993) — and as early as Strömgren (1963!) — that there is no clear-cut dependence of metallicity on age for at least the thin disk, while a large, significant scatter exists at all ages. And as shown earlier (Nordström et al. 1999), diffusion of the Galactic orbits of the stars is an unlikely explanation of this situation. Clearly, even the solar neighbourhood is a much more complicated and interesting subject than ever before.

Looking ahead a decade from now, *Gaia* (Perryman et al. 2001) and RAVE (Steinmetz 2003) should provide the next quantum leap in our knowledge of the Galaxy. The present material should remain useful, not only for studying our Galaxy in the meantime, but also when optimising the observing and data reduction strategies of those projects.

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