A Livelier Picture of the Solar Neighbourhood

The formation and evolution of galaxies is one of the great outstanding problems of modern astrophysics. A new radial-velocity survey of over 14,000 nearby, long-lived stars now documents the history of the Solar neighbourhood in unprecedented detail – and severely challenges models for the evolution of galactic disks.

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Spiral galaxies are an important part of the visible Universe, and the prototype is our own Milky Way. Our central vantage point is ideal for observing the most important component of Milky Way and any other spiral galaxy – the disk. And the numbers, ages, detailed chemical compositions, and galactic orbits of nearby, long-lived disk stars carry vital information on its evolution (Freeman & Bland-Hawthorn 2002).

In the Solar neighbourhood we can determine these parameters for stars from the entire history of the disk with a completeness and accuracy not available anywhere else in the Universe. The stars in the Solar neighbourhood therefore provide a fundamental benchmark for all theoretical models of the chemical and dynamical evolution of galaxy disks.

For truly incisive tests of the models we need space velocities and galactic orbits, metal abundances, ages, and binary star identification for a large, complete sample of long-lived stars. Until now, stellar samples were either complete but key data were missing, or the data were complete but the sample suffered from serious selection biases. Both cases may lead to wrong results.

The Geneva-Copenhagen Survey

The Geneva-Copenhagen Survey of the Solar Neighbourhood (Nordström et al. 2004) was designed to provide a new, superior basis for our understanding of the evolution of the Milky Way disk. For the first time, we have obtained accurate, multiple radial velocity observations for a large, complete, and unbiased sample of over 14,000 long-lived stars near the sun. These have been combined with other data and new calibrations to compute complete space motions, Galactic orbits, metallicities, and ages for all the stars. Binary stars (34% of the sample) are identified as well.

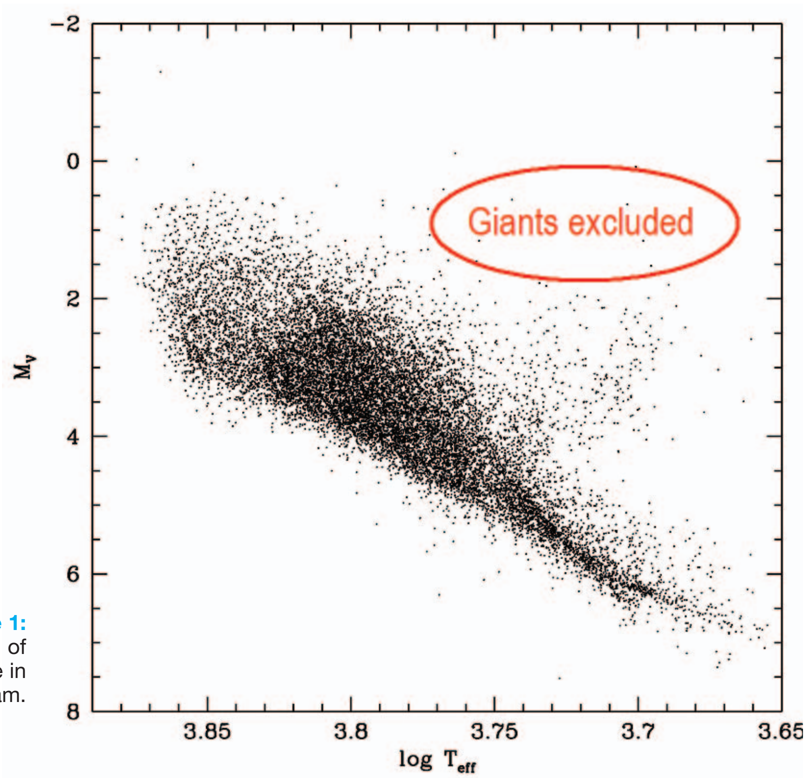

Figure 1: Distribution of the sample in the HR diagram.

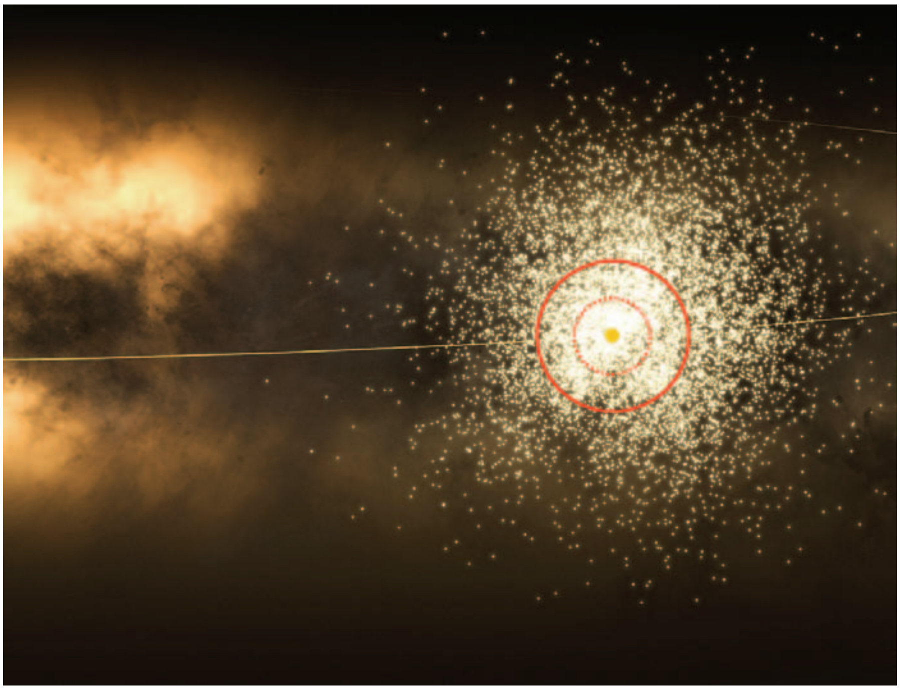

Figure 2: Artist's impression of the 3D distribution of the sample around the sun (cutaway view for clarity). The completeness distance of 40 pc is indicated by the dotted circle (courtesy Lars Christensen, ST/EcF).

The foundation for the survey was laid in the 1970s and 1980s by Bengt Strömgren and Erik Heyn Olsen. All stars of HD spectral type A5 to late G in the entire sky and brighter than visual magnitude ~8.5 were measured in the Strömgren $uvby\beta$ colour system, largely with the Danish 50cm telescope at La Silla - some 30,000 stars in total (Olsen 1994 and earlier papers).

From this photometry a complete sample of 16,682 F and G-type dwarf stars could be defined without any bias with regard to metal abundance or kinematics (see Fig. 1). The sample is defined by limiting apparent magnitude, but in such a way as to be essentially volume complete to a distance of 40 pc, while the brighter stars reach distances of 2-300 pc (Fig. 2).

Distances, metal abundances, and ages can be determined from the photometry, as outlined below. Proper motions – hence the velocity components in the plane of the sky – were available from the Hipparcos and TYCHO-2 astrometric catalogues. The “missing link” was the space motion component along the line of sight – the radial velocity.

A precise radial velocity completes the full 3D space motion vector of the star. Any variation of the radial velocity signals a binary star, for which the photometric values of distance, age, and metal abundance will be wrong.

However, multiple radial velocity measurements of many thousands of stars from conventional photographic spectra required such large amounts of telescope time that the task had long been considered impossible. Therefore, existing radial-velocity samples were biased towards ‘interesting’ kinds of stars, potentially introducing artificial correlations between age, metallicity, and kinematics.

However, the Geneva-Marseille radial-velocity spectrometer CORAVEL (Baranne et al. 1979) brought together cross-correlation spectroscopy, a low-noise photoelectric detector, and a computerised system for instrument control and data collection. This was the efficient tool needed to do the job right. The first CORAVEL was commissioned at the Swiss 1m telescope at Observatoire de Haute-Provence (OHP), France, in 1977, and it was agreed to place the second one at the Danish 1.5m telescope on La Silla. In 1981 our all-sky survey was initiated at both telescopes (see Fig. 3).

A Thousand and One Nights

Obtaining over 60,000 CORAVEL observations of more than 14,000 programme stars was still a huge task, requiring over 1,000 clear observing nights between the two telescopes. But the rapid scanning rate of CORAVEL made the instrument almost insensitive to sky conditions, so every night a star could be seen anywhere in the sky was usable. Veterans of La Silla may still remember gazing in amazement at the open dome of the Danish 1.5m on many a night when all other observers were fast asleep…

In view of later developments for the VLT, it is interesting to note that the CORAVEL team introduced flexible scheduling and service observing on La Silla long before those terms had even been coined. Several joint programmes were conducted in parallel, ranging from Cepheids and supergiants in the Magellanic Clouds over the detailed kinematics of 47 Tuc and ω Cen to all-sky programmes of bright field stars, such as ours.

When the seeing was good and the faint objects were up, or when observations at particular phases were needed, the observationally demanding programmes had priority; otherwise our bright stars got done. We

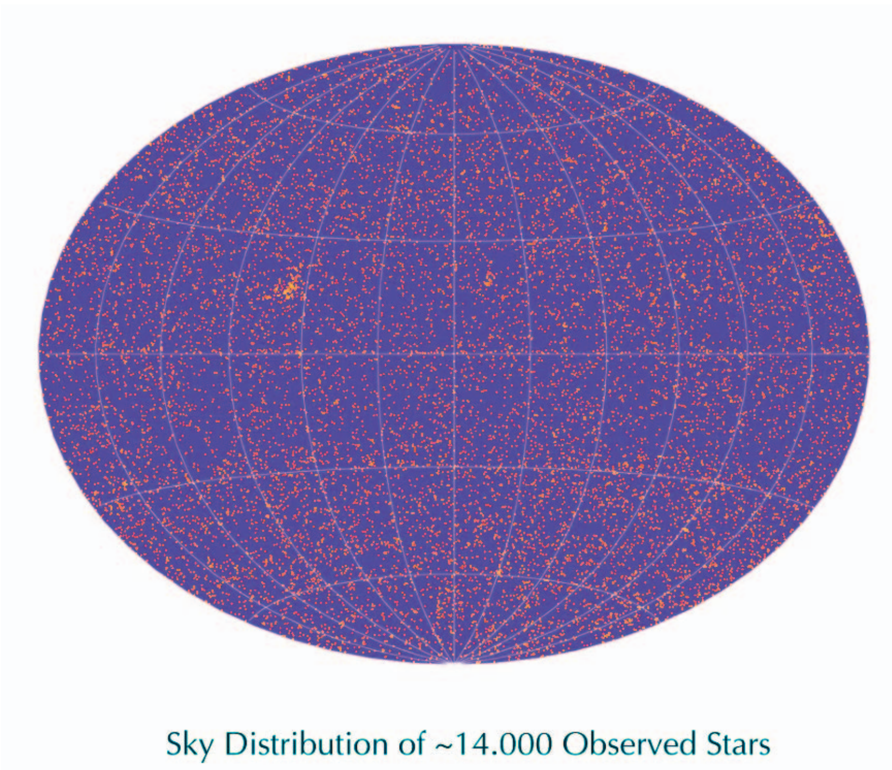

Figure 3: The Geneva-Copenhagen survey stars projected on the sky (note the Hyades cluster at upper left).

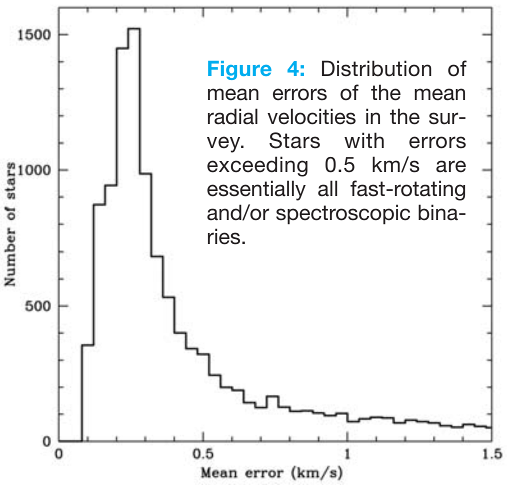

Figure 4: Distribution of mean errors of the mean radial velocities in the survey. Stars with errors exceeding 0.5 km/s are essentially all fast-rotating and/or spectroscopic binaries.

owe a great debt of gratitude to the many colleagues who thus contributed to our programme at both telescopes.

The hardware correlation mask in CORAVEL is optimised for sharp-lined late-type stars. For the fast-rotating early F stars on our programme (v sin$i \geq 30$ km/s), it gave results of poor accuracy – if any at all. Most of these stars were therefore reobserved at the Harvard-Smithsonian Center for Astrophysics (CfA), USA, where digitally recorded spectra correlated with synthetic templates yield good radial velocities for rotations up to 140 kms-1 (Nordström et al. 1997). The resulting radial velocities are of superb accuracy, with a typical mean error of 0.25 km/s (Fig. 4) – some 20 times better than those to be obtained from the GAIA mission. In order to identify spectroscopic binaries, the average star has 4 observations obtained over 1–3 years, but some have data extending over 10–15 years. Overall, we find 3,223 (19%) spectroscopic and 3,537 (21%) visual binaries of all kinds in the sample, for a total binary count of 5,622 (34%; some stars are in both categories).

Distances, Space Velocities, and Galactic Orbits

Photometric distances from the *uvby* photometry were compared with the Hipparcos results for stars with parallaxes better than 3%. We found that the photometric distances had an accuracy of 13% and no significant systematic errors. Thus, photometric distances were used if the Hipparcos parallax was worse than 13% or not measured at all, so all distances should be accurate to about this value.

Proper motions were taken from the TYCHO-2 catalogue. Together with the distances and radial velocities, they yield full 3D space motions U, V, W with an accuracy of about 1.5 km/s in each component. These, in turn, were used to compute the orbit of each star in its motion around the Galactic centre, assuming a smooth gravitational potential satisfying the observational constraints provided by the Galactic rotation curve and the local matter density. Within these assumptions, the motion of a star can be followed for two Galactic rotations backward and forward in time – still much shorter than the average lifetime of the stars.

Metallicities and Effective Temperatures

The metal content of F and G dwarfs can also be derived from the Strömgren photometry, using a suitable calibration. We have checked the existing metallicity calibrations and consolidated and extended them to the highest and lowest temperatures seen in our sample, using reliable spectroscopic analyses for comparison. The resulting metallicities have an accuracy of 0.1 dex over the whole temperature range.

Effective temperatures are needed in order to compute ages for the stars. They were derived from the reddening-corrected Strömgren photometry through the calibration of Alonso et al. (1996).

Computing Ages

Computing ages for our sample, which extends back to the formation of the disk 10 Gyr ago or more, is a far more complex task. The only reliable method is to fit stellar evolution models (isochrones, from Girardi et al. 2000) to the observed stellar parameters – simple in principle, but not so in practice.

If a star has not evolved perceptibly in the HR diagram its age is basically indeterminate; and most evolutionary changes remain fairly small relative to typical observational errors. Moreover, the strong variation in speed of evolution over the HR diagram combines with the prior distributions in mass, absolute magnitude, and metal abundance in subtle ways. This can lead to large systematic errors in the ages and completely misleading estimates of their true reliability and accuracy.

Our stellar ages were determined by considering the three-dimensional HR 'cube' (T_{eff}, M_V, [Fe/H]). For each point in the cube, we computed the probability that the observed star could be located there and have the age of the isochrone passing through that point, given the observational errors. These probabilities were integrated in a Bayesian manner over the whole cube, taking the *a priori* distributions of masses, etc. into account.

The result is an *a posteriori* probability density distribution for the possible ages of the star. This so-called 'G function' is normalised to 1 at the maximum, which denotes the most likely value of the actual age (Fig. 5). The method is described in more detail by Jørgensen & Lindegren (2004); it is similar in many respects to that of Pont & Eyer (2004), but differs in some numerical respects and in the calibrations and corrections applied to the data and the models.

The points where the G function drops to the value 0.6 define the ±1σ error limits for the ages. If both are inside the age range of the models (0–17.8 Gyr) we call the age 'well-defined', and both are given in the catalogue (the error can still be large, but at least its value is reliably known!). If one of the limits is outside the range of the isochrones, only an upper or lower age limit is given, and none at all if the G function is too flat to go below 0.6 anywhere in the range.

In this manner, ages of any quality are determined for 13,636 of our total of 16,682 stars, 11,445 of which are 'well-defined'. If we limit the sample to the 11,060 single stars, 7,566 have well-determined ages, out

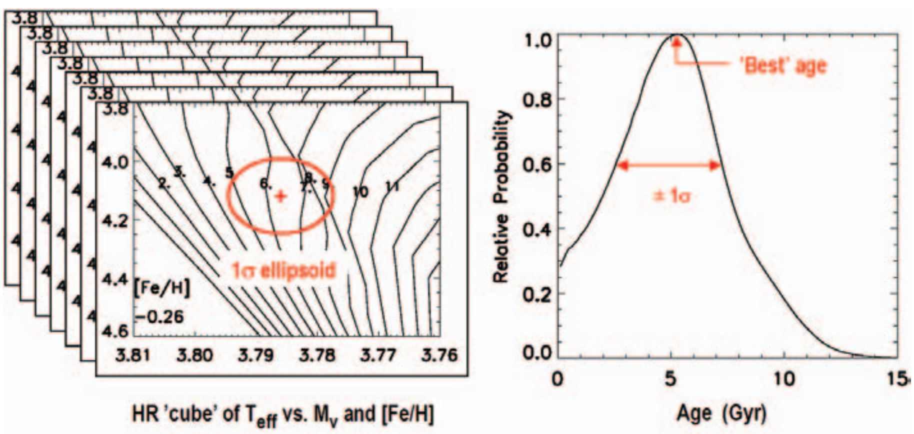

Figure 5: For every point inside and outside the error ellipsoid in the HR 'cube' (left), the probability that the observed point could fall there is computed. Taking statistical biases into account, this is integrated to form the G function (right), i.e. the probability that the star has any given age in the interval covered by the isochrones.

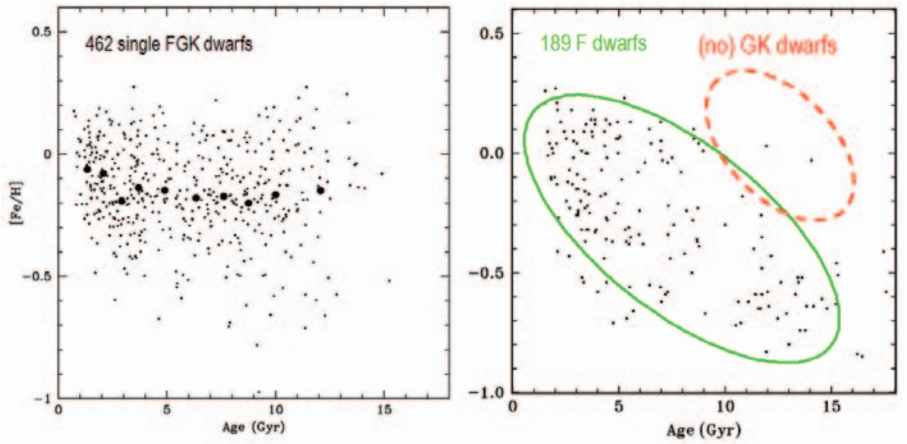

Figure 6: Age-metallicity diagrams for all single stars within 40 pc and with well-defined ages (left), and for the stars of Edvardsson et al. (1993, right).

of which 6,144 have ages better than 50% and 3,528 better than 25%.

We emphasise that because the conditions for accurate determinations vary dramatically across the HR diagram, the stars with (good) ages are not a representative sample of the Solar neighbourhood as a whole.

Classical Tests of Classical Models

The classical type of Galactic evolution models consider the disk to be a rotationally symmetric, well-mixed system, adequately described by the variation of mean chemical composition and kinematics with age and distance from the Galactic centre. Stars are assumed to be born with a constant Initial Mass Function and at specified rates over time, evolve, die, and gradually enrich succeeding generations of stars in heavy elements. The delay after which the two supernova types explode may be included, and infall of intergalactic gas may be added as another parameter.

Meanwhile, massive objects in the disk – perhaps spiral arms or giant molecular clouds – perturb the circular motions of the newborn stars and cause their random velocities to increase with time ('dynamical heating').

Such models yield specific, single-valued predictions for the variation of metallicity and kinematics as functions of age and radius in the disk. Thus, their degree of realism can be tested by comparison with samples of local stars with accurate data. But the samples must be large and cover the age of the disk, the data must be complete and accurate, and correlations between the parameters we want to study must not be built in.

As summarised above, this is exactly what we have strived to achieve. But before we describe the actual tests, it is worth pointing out that the importance of the radial velocities extends far beyond the computation of velocity dispersions:

First, they allow us to identify – and if need be, eliminate – the spectroscopic binaries for which neither metallicity, age, nor space motion is reliable. Second, the velocities distinguish the 'transit passengers' from far away from the stars that have spent their life in our neighbourhood and contributed to its evolution. And third, they allow us to correct the frequencies of different stellar groups for the speed with which they cross the little volume around the sun that we have observed.

The 'G Dwarf Problem'

The first classical test of the models is the metallicity distribution of long-lived stars that can survive from the formation of the disk. The long-standing 'G dwarf problem' (van den Bergh 1962) refers to the observed lack of old, metal-poor dwarf stars that should have formed in large numbers together with the massive stars that produced the heavy elements we observe in the younger generations.

The problem was re-examined by Jørgensen (2000), who found that the deficit of metal-poor dwarfs was even more marked in our complete, unbiased sample: Our part of the disk certainly did not evolve as a closed system!

The Age-Metallicity Relation

The second classical test of the models is the gradual rise of metallicity with time, as new heavy elements are synthesised in stars and built into the following generations – the so-called Age-Metallicity Relation (AMR). The key features here are the shape of the average relation and the amount of scatter around it. Key questions are whether variation of the mean is consistent with the gradual enrichment picture, and whether a mean relation describes the distribution of the observed values adequately when the observational uncertainty is accounted for.

Figure 6 shows the AMR for our volume-complete subsample of stars within 40 pc and with 'well-defined' ages. Larger samples have been studied, but the conclusion is the same: There is no significant change in mean metallicity in the Solar neighbourhood over the past ~10 Gyr, and the scatter in [Fe/H] at all ages greatly exceeds the observational error of ~0.1 dex. Scatter is the key message here, not any 'mean trend', and classical models cannot explain it.

Figure 6 contrasts our result with the much-quoted spectroscopic study of 189 of our F dwarfs by Edvardsson et al. (1993). The two studies were planned to be complementary - exquisite detail vs. completeness and freedom from bias - and together they

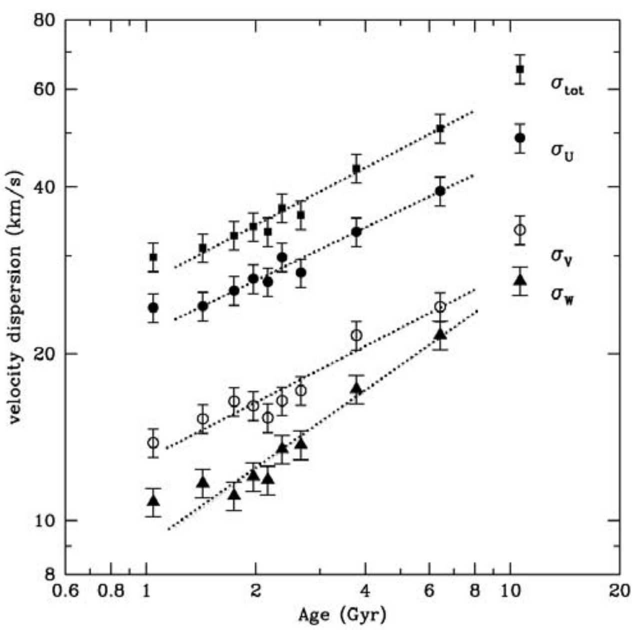

Figure 7: Velocity dispersions as a function of age for 2,852 single stars with ages better than 25%.

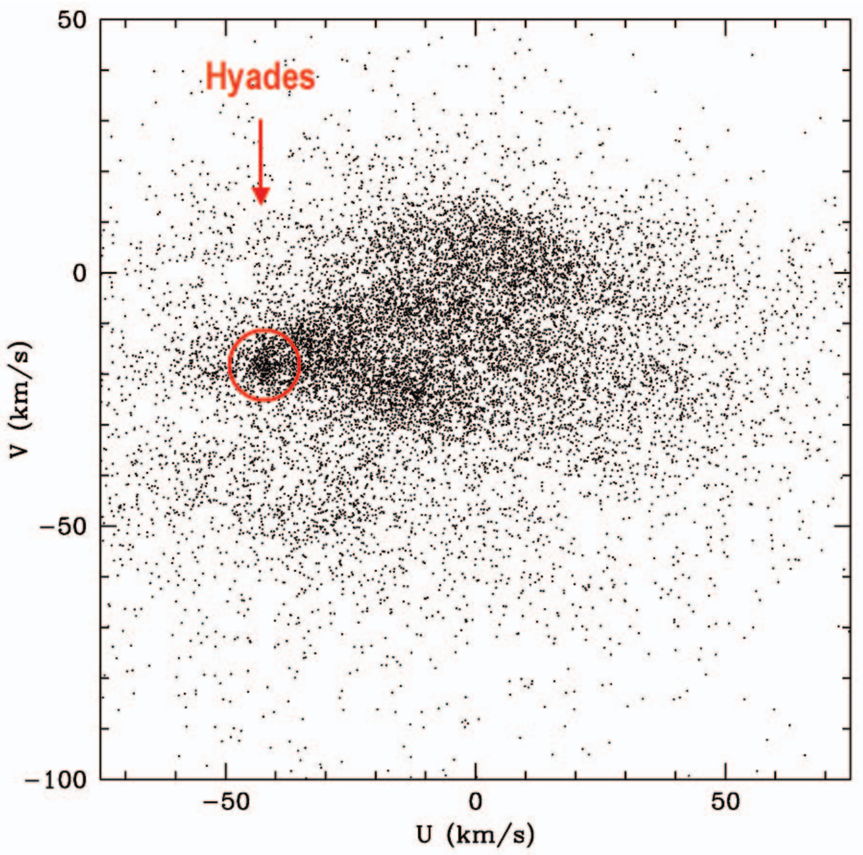

Figure 8: U-V diagram for all the stars in the sample.

provide very strong constraints on models of the evolution of our Galaxy.

It is obvious that the scatter in [Fe/H] is at least as large for their data as for ours, but their sample of F stars automatically excluded any old, metal-rich stars from consideration – a limitation recognised by Edvardsson et al. (1993) themselves. Accounting for this, the two diagrams are in fact consistent, although both ages and metallicities were obtained by quite different techniques.

The Local Dynamical Evolution

Figure 7 shows the velocity dispersions as functions of age for the stars with the best-determined ages in the sample. The slope of the relations is intermediate between earlier results and shows that (i) radial mixing of stellar orbits cannot explain the scatter in the AMR; (ii) the classical disk heating mechanisms cannot explain the observed results; but (iii) all kinematic traces of any dwarf galaxies that might have merged with the Milky Way in its early stages should be erased by now.

Finally, as Fig. 8 shows, the velocity distribution of the stars in our neighbourhood is far from smooth, but shows marked, discrete features. The stars in these have a broad range of both metallicities and ages. Thus, they were not simply formed together but are the result of dynamical focusing, probably from passing through a spiral arm.

This implies that, e.g. identifying local stars of the thick disk by Gaussian decomposition of the velocity distribution is risky at best. Further, a smooth, symmetric gravitational potential seems inadequate for computing stellar orbits for more than a short time span into the past or the future.

Conclusions and Outlook

As we have seen, classical disk evolution models spectacularly fail every classical test when confronted with our data: Neat sharp lines simply do not describe even the main features of the story correctly.

An entirely new generation of 3D models is needed, including real physical descriptions of the (hydro)dynamics of star formation, supernova explosions, and galaxy mergers. But it will be a long time before their numerical resolution is sufficient to match the full detail of our new picture of the Solar neighbourhood.

As a test sample for such models, the Geneva-Copenhagen survey will remain unique for many years: No similarly large set of accurate radial-velocity data for an astrophysically selected sample of stars exists, and none is planned. While the ESA cornerstone mission GAIA will provide many more radial velocities around 2015, their precision will be 20 times lower than ours, making binary star detection notably less complete than in our survey.

Acknowledgements

Our survey was made possible by large grants of observing time at the Danish 1.5m telescope on La Silla and the Swiss telescope at OHP, and by the collaboration of several colleagues from ESO, Marseille, and our own institutes. Dr. David W. Latham and colleagues at the Center for Astrophysics contributed the lion's share of the data for the early F stars. Financial support received from the Danish and Swedish Research Councils and the Fonds National Suisse pour la Recherche Scientifique was of vital importance, as was that from the Carlsberg Foundation, the Smithsonian Institution, the Nordic Academy for Advanced Study, and the Nordic Optical Telescope Scientific Association. Without it, our survey could never have been conceived, let alone completed.

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