The evolution of the Milky Way monitored in the solar neighbourhood

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Abstract. In this review we concentrate on the dynamical evolution of the Milky Way as monitored in the solar neighbourhood. The relevant data sets are presented and discussed in detail. In the second part we review various mechanisms, which drive the dynamical evolution.

1. Dynamical evolution of the galactic disk traced in the solar neighbourhood

The key data set, which we use for this study, is the Fourth Catalogue of Nearby Stars (hereafter referred to as CNS4), which has been now completed in its preliminary form (cf. Jahreiß et al. 1998, 1999). The catalogue represents the most complete inventory of stars within a distance of 25 pc from the Sun. It contains data of about 3000 stars, most of them improved by Hipparcos (ESA 1997) parallaxes. For instance, the parallaxes of 1411 stars out of the 1761 stars with parallaxes more accurate than 10% are Hipparcos measurements. Statistical tests have shown that the CNS4 is complete for stars with absolute magnitudes $M_V \leq 8^{m}$, which includes the K stars. For M stars the CNS4 becomes increasingly incomplete and kinematically biased towards high proper motions.

Fig. 1 illustrates the kinematical evolution of the galactic disk, where the total velocity dispersions of the peculiar velocities of the stars, i.e. the quadratical sum of the dispersions of the three velocity components, are plotted versus the ages of the stars. For this purpose we have extracted three data sets from the CNS4. The first set includes all main sequence stars down to late type K stars with known space velocities. These have been grouped according to $B-V$ colour and the age of each group is assumed to be one half of the average main sequence life time of the stars, or for long lived late type stars one half of the age of the galactic disk, for which we have adopted a value of 10 Gyrs (cf. also Jahreiß et al. 1998, 1999). The second set of stars is given by the McCormick K and M dwarfs with known space velocities. The McCormick stars have been detected by an objective prism survey (Vyssotsky 1963) and are thus free of kinematical bias. Their ages can be determined using the emission intensities of the emission kernels of the Calcium H and K absorption lines, because the emission intensity decreases with increasing age of a star. Emission intensities have been indexed by Wilson & Woolley (1970) for almost 300 McCormick stars on a relative scale. Grouping the stars according to their emission indices and
assuming a constant star formation rate allows one then to estimate the mean age of each group (Wielen 1974). In this way older age groups with ages larger than 5 Gyrs can be resolved. The third set of stars consists of 206 main sequence stars with $0.5 \leq B-V \leq 1$ (spectral type G and K), for which the chromospheric emission has been measured with the Mt.Wilson H and K spectrophotometer (Soderblom et al. 1991). S–measures can be transformed according to Noyes et al. (1984) to log $R'_{\text{HK}}$. These can be used again as age estimators and have been calibrated quantitatively by Donahue (1998) on an absolute age scale. Finally the velocity dispersion of young Cepheids is shown as normalization. All velocity dispersions shown in Fig. 1 have been calculated by weighting the velocity components of each star by the absolute value of its vertical velocity $|W|$ and are thus representative for a cylinder perpendicular to the galactic plane at the Sun’s position (Wielen 1974 and cf. section 3 below). As can be seen from Fig. 1 all three independent data sets give a consistent picture of the rise of the velocity dispersion. The diagram in Fig. 1 can be read from the right to the left and vice versa. In the former case one relates the velocity dispersions of the stars to their epoch of formation. They would reflect then the conditions of the interstellar matter at their birth. However, one would expect then a different evolution of the velocity dispersions from what is observed. In particular, the sudden drop of the velocity dispersions of the youngest stars with ages less than 2 Gyrs would single out the present epoch, which violates the cosmological principle (Wielen 1977). Since the work of Spitzer & Schwarzschild (1951, 1953) it is generally believed that the diagram has to be read from the left to the right, i.e. that the velocity dispersions of the stars depend on the ages of the stars. The rise of the velocity dispersion reflects then stochastical accelerations of the stars by massive perturbers, which lead to diffusion of stars in velocity space. The solid line drawn in Fig. 1 indicates an empirical fit to the data of the form

$$
\sigma_v = \sqrt{\sigma^2_{v0} + C\tau},
$$

with $\tau$ the age of the stars.

2. Comparision of CNS4 data with other modern data sets

We have compared our kinematical data with the data of the Edvardsson et al. (1993) sample of nearly 200 F and G stars with measured space velocities and very accurately determined metallicities. In Fig. 2 the Edvardsson et al. data are shown as scatter plots. The gradual widening of the distributions with increasing age of the stars can be clearly seen. Beyond 11 Gyrs the distributions widen abruptly and the mean rotational velocity of the stars lags about 40 km/s behind that of the younger stars. This is typical for stars of the thick disk and we interpret this abrupt change as the transition from the old thin disk to the thick disk. The separation of thick disk from old thin disk stars found here is consistent with other studies of the thick disk (cf. Gilmore’s article in this volume), which also show that the thick disk is old. In the following we concentrate on the dynamical evolution of the old thin disk.

We have grouped the Edvardsson et al. (1993) stars into age groups and have calculated $|W|$–weighted velocity dispersions for each group. These are also
shown in Fig. 2 overlaid over the CNS4 data. For this purpose we have increased the age scale of the solar neighbourhood data by 10% to that of Edvardsson et al. (1993). From the comparison we conclude that both data sets are entirely consistent with each other.

Recently Dehnen & Binney (1998) have constructed a new important sample of kinematical data. By careful comparison of the Hipparcos and Tycho catalogues (ESA 1997) they were able to extract from the Hipparcos catalogue a kinematically unbiased sample of more than 14000 stars for which reliable parallaxes and proper motions are available. Dehnen & Binney (1998) had no radial velocities available, but making use of the many thousand viewing angles through the velocity ellipsoid they determined velocity dispersions of groups of stars grouped according to their $B - V$ colour. These are reproduced in Fig. 3, where also the corresponding CNS4 data are shown, which refer now to the local volume and have been thus not weighted by $|W|$. The interpretation of the diagrams is that stars bluer than $B - V = 0.6$ are younger than the age of the disk, so that the rise of the velocity dispersions and the increasing rotational lag reflect the dependence of the velocity dispersions and the rotational lag on the ages of the stars. Beyond $B - V = 0.6$ the main sequence life times of the stars are larger than the age of the disk and the curves level off at Parenago’s discontinuity. It should be kept in mind that a group of stars of given colour always contains a mixture of young and old stars. As Fig. 3 shows also the Dehnen & Binney (1998) data are in perfect agreement with the solar neighbourhood data. More recently Binney et al. (2000) have derived from their data a velocity dispersion – age relation making use of the Padua isochrones and experimenting with various star formation histories. Their preferred result is shown in Fig. 4 in comparison with the solar neighbourhood data for which again the age scale has been increased by 10%. Formally the Binney et al. (2000) relation is described by a $\sigma_{tot} \propto \tau^{0.33}$ law, while the solar neighbourhood data are better described by a $\sigma_{tot} \propto \tau^{0.5}$ relation. But the implied discrepancy is only very mild. In particular Binney et al. (2000) confirm the high values of the velocity dispersion of the old disk stars. Rocha–Pinto (priv. comm.) has analyzed yet another sample of late type stars and finds a velocity dispersion – age relation, which is also similar to the CNS4 data.

Taking all this together, we conclude that all modern data sets on the kinematics of nearby stars are in excellent agreement. Finally we note that very recently Quillen & Garnett (2000) have presented a velocity dispersion – age relation, which is at variance with the results described here. This appears to be related mainly to the $V$ velocity dispersions derived by them and is at present not understood.

3. Star formation history traced in the solar neighbourhood

The sample of G and K dwarfs from the CNS4 with individually determined ages using their chromospheric HK emission fluxes as described in section (1) can be used to trace the star formation history of the galactic disk. The star formation rate is defined per vertical column density. Thus to each star detected in the local volume a weight has to be assigned, which accounts for the number of similar stars expected in the cylinder perpendicular to the galactic plane at
the Sun’s position. Obviously the weight must be inversely proportional to the
detection probability, which is given by the crossing time of the star through the
local volume divided by the period of the vertical oscillation of the star. If the
vertical oscillations are assumed to be harmonic, the oscillation periods of all
stars are the same, and the weight is simply given by the absolute value of the
vertical midplane velocity $|W|$. In Fig. 5 a cumulative diagram of the weights is
shown, which illustrates the growth of the surface density of the disk with time.
The slope of the curve is the star formation rate. As can be seen from Fig. 5 there
are hardly any stars older than 7 Gyrs, for which apparently the chromospheric
flux dating cannot be applied. For the younger stars the star formation rate is
fairly constant with a break at an age of the stars of 3.5 Gyrs. The ratio of the
slopes is 1 : 3, indicating an enhanced star formation rate at earlier epochs
of the evolution of the galactic disk. Due to the non-linear $K_z$ force law the actual
vertical oscillations of the stars are not harmonic. We have performed numerical
integrations of stellar orbits in a realistic model of the potential of the galactic
disk as determined by Flynn & Fuchs (1994). The resulting oscillation periods
depend on the vertical midplane velocity as

$$T(|W|) = T_0 \cdot (1 + 0.016|W|).$$

If this correction to the weights is taken into account, the break in the star
formation becomes more pronounced with a ratio of slopes of 1 : 3.7.

Star bursts appear as ‘steps’ in the cumulative diagram. Hernandez et
al. (2000) have applied their method to reconstruct the star formation history
to a sample of bright stars in the solar neighbourhood. They were able to
trace the star formation history back over 3 Gyrs and found three bursts of star
formation at $\tau = 0.5, 1.3, \text{ and } 2$ Gyrs, respectively. These can be seen also
distinctly in the cumulative diagram in Fig. 5. There are also ‘steps’ at earlier
times, which are probably related to star bursts in the evolution of the galactic
disk. They correlate, however, only in part with the star burst periods proposed
by Rocha–Pinto et al. (2000).

4. Disk heating mechanisms

Since the pioneering papers by Spitzer and Schwarzschild (1951, 1953) there is
a very rich literature on disk heating, which can not be reviewed here in its
entirety. The many proposed disk heating mechanisms can be grouped loosely
in the following way:

1. Fast massive perturbers of the disk from the galactic halo
Such objects deflect disk stars by gravitational encounters, when they pass
through the disk, and thus heat the disk stochastically. The diffusion coefficients,
which describe the resulting diffusion of the stars in velocity space quantitatively,
are proportional to the typical length of an encounter. This is inversely propor-
tional to the typical relative speed between disk stars and massive perurbers.
For massive perturbers from the halo this relative speed is dominated by their
velocities and one expects a diffusion coefficient, which is independent of the
speed of the stars (Wielen 1977),

$$\frac{d\sigma^2}{d\tau} = \text{const.}, \quad \text{implying} \quad \sigma^2 \propto \tau.$$
Such type of disk heating mechanisms lead to the velocity dispersion–age relation, which we have shown in section 1 fitted to the data. Massive black holes have been proposed as candidates for such kind of perturbers (Lacey & Ostriker 1984). This scenario has been given up in the meantime, however, because such massive black holes, which are thought to be of primordial nature, would have destroyed the much more fragile disks of dwarf spiral galaxies (Rix & Lake 1993, Fuchs et al. 1996). Recently Moore et al. (1999) have shown by extensive numerical simulations that, if the dark halos were assembled according to the cold dark matter (CDM) cosmology, they would be highly clumped. According to their simulations about 10% of the dark matter is clumped to lumps with typical masses of $5\times10^8 \ M_\odot$ and sizes of 10 kpc (Moore, priv. comm.). The core radii of the lumps are somewhat uncertain, because they are of the order of the spatial resolution of the simulations, typically 1 kpc. We have run numerical simulations of the disk heating effect due to such lumps using a sliding grid scheme with periodic boundary conditions (Fuchs et al. 1994). The central grid frame represents a patch of the galactic disk and is populated by test stars, which are referred into the central frame, when they leave this, as if entering from neighbouring grid frames, which slide along the central frame (see also the contribution by Hänninen & Flynn in this volume). This model disk is then exposed to perturbations by the dark matter lumps modelled as Plummer spheres on isotropic orbits with parameters as found by Moore et al. (1999). The resulting disk heating effect is illustrated in Fig. 6. By varying the core radii we found that the amplitude of the growth of the velocity dispersion depends very much on the adopted core radii and is, thus, at present not well constrained. Striking, however, are the large bulk motions of the stars induced by the dark matter perturbations. By analyzing the simulations we could identify each of the sudden jumps of the mean velocities of the test stars with the passage of a perturber through the model disk. The implied mean velocities are much larger than actually observed, and would present a severe challenge to CDM cosmology, if the results of Moore et al. (1999) are indeed correct.

2. Slow massive perturbers of the disk such as molecular clouds
In that case the diffusion coefficients are inversely proportional to the typical stellar peculiar velocity, because the molecular clouds are essentially at rest in the corotating frame,

$$\frac{d\sigma^2}{d\tau} = \frac{\text{const.}}{\sigma}, \quad \text{implying} \quad \sigma^2 \propto \tau^{1/3}. \quad (4)$$

Actually the molecular clouds form a thin layer, and since the disk stars spend most of the time out of this layer, the disk heating becomes even more ineffective (Lacey 1984), $\sigma^2 \propto \tau^{1/4}$. In one of the panels of Fig. 7 we show the result of a numerical simulation with the sliding grid scheme described above of the disk heating effect due to molecular clouds. The adopted parameters are: mass of a molecular cloud $5\times10^5 \ M_\odot$, Plummer radius 20 pc, the vertical scale height of the cloud layer 55 pc, and surface density of the molecular clouds $2.5 \ M_\odot \text{pc}^{-2}$. As can be seen from Fig. 7 the disk heating effect due to molecular clouds is in the solar neighbourhood negligible. It should be kept in mind, however, that molecular clouds are very effective in deflecting stellar orbits (Lacey 1984). If the main heating mechanism affects mainly the planar velocity components
like density waves, for example, the molecular clouds establish the W velocity distribution.

Finally we only enumerate:

3. Transient spiral arms (Sellwood & Carlberg 1984, Binney & Lacey 1988)
4. Infalling, disrupting satellite galaxies (see Velazquez and White (1999) for a recent paper)

5. Tracing the dynamical stability of the galactic disk

The criterion of stability of galactic disks against gravitational instabilities is described quantitatively by the Toomre stability parameter

\[ Q = \frac{\kappa \sigma_U}{\alpha G \Sigma_d}, \]

where \( \kappa \) denotes the epicyclic frequency of the stellar orbits, \( \sigma_U \) the radial velocity dispersion of the stars, \( G \) the constant of gravity, and \( \Sigma_d \) the surface density of the disk, respectively. \( \alpha \) is a numerical coefficient ranging from 3.4 for a stellar disk with a Schwarzschild velocity distribution function (Toomre 1964) to 3.9 for a stellar disk with an exponential velocity distribution function (Fuchs & von Linden 1998). For an isothermal gas disk the coefficient is given by \( \alpha = \pi \). As is well known, the requirement for dynamical stability is

\[ Q \geq 1. \]

Galactic disks are compound systems of the stellar and the interstellar gas disks. Since the compound disk is more unstable than each disk taken alone, the requirement for dynamical stability of a compound disk is

\[ Q_s > 1, Q_g > 1. \]

Quantitative relations are given, for instance, by Fuchs & von Linden (1998). The violation of this condition has severe implications for the dynamics of the disk. Fuchs & von Linden (1998) have carried out numerical simulations of the dynamical evolution of such an unstable compound stellar and interstellar gas disk. Initially only the gas disk was assumed to be unstable \((Q_s > 1, Q_g < 1)\). Both the stellar and the gas disk react violently to this condition by developing many strong short-lived, shearing spiral arms. The ensuing disk heating effect is very large. The stellar disk heats up within a Gyr so much that it becomes dynamically totally inactive. Only star formation of stars on low velocity dispersion orbits can prevent this rapid heating. The numerical simulations of Fuchs & von Linden (1998) indicate that, if the star formation rate is of the order \( \dot{\Sigma}_d / \Sigma_d \approx 0.3 \text{Gyr}^{-1} \), the stellar disk stays cool enough to show well developed spiral structure, although the velocity dispersion of the old stars is continuously rising.

It is instructive to trace the dynamical stability of the galactic disk back in time. For this purpose we have back extrapolated the run of the surface densities of the stars and the gas as well as the stellar velocity dispersion. The build up
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of the surface density of the stars can be determined using the star formation law $\Sigma_d$ discussed in section 3,

$$\Sigma_* (t) = \Sigma_* (T) - \int_t^T \dot{\Sigma}_* (t') dt',$$  \hspace{1cm} (8)$$

where a present surface density of $\Sigma_* (T) = 35 \, M_\odot \, pc^{-2}$ (Holmberg & Flynn 1998) and a present star formation rate of $0.9 \, M_\odot \, pc^{-2} \, Gyr^{-1}$ is adopted. The age of the disk is assumed as $T = 11$ Gyrs. The star formation rate is back extrapolated according to Fig. 5 for stars younger than 7 Gyrs and it has been adjusted for the older stars as described below. The surface density of the gas at earlier epochs is determined by star formation and accretion of fresh gas,

$$\Sigma_g (t) = \Sigma_g (T) - \int_t^T (\dot{\Sigma}_{g,accr} (t') - \dot{\Sigma}_* (t')) dt',$$  \hspace{1cm} (9)$$

where the accretion rate is described by an exponential law, $\dot{\Sigma}_{g,accr} \propto \exp (-t'/t_a)$. A present surface density of cold star forming interstellar gas of $8 \, M_\odot \, pc^{-2}$ (Dame 1993) is adopted, while the present day accretion rate and the accretion time scale are left as further free parameters. In the best fitting model shown in Fig. 7 we adopt $\dot{\Sigma}_{g,accr} (T) = 0.6 \, M_\odot \, pc^{-2} \, Gyr^{-1}$ and $t_a = 16$ Gyrs. The present day star formation and accretion rates chosen here are consistent with independent determinations as tabulated in Thon & Meusinger (1998). The average velocity dispersion of the stars at a certain epoch can be determined directly from the observed velocity dispersion age – relation,

$$\sigma_U (t) = \frac{1}{t} \int_0^t \sigma_U (\tau) d\tau .$$  \hspace{1cm} (10)$$

In order to check the plausibility of the model and to constrain the free parameters, we have also calculated the evolution of the metallicity $Z$ by integrating the enrichment equation,

$$\frac{\dot{Z} (t)}{Z (T)} = \frac{y}{Z (T) \Sigma_g (t)} - \frac{Z (t) \dot{\Sigma}_{g,accr} (t)}{\Sigma_g (t)},$$  \hspace{1cm} (11)$$

backwards in time. Equation (11) is based on the instantaneous recycling approximation and we interpret the metallicity calculated in this way as usual as representative for the $[O/H]$ abundance. $[O/H]$ is converted to $[Fe/H]$ by the empirical relation $[Fe/H] = 1.43 \, [O/H]$ (Sommer-Larsen & Yoshii 1989). A mean present day metallicity of 0.05 dex is adopted and a yield of $y/Z_\odot = 0.66$ (reduced by 10% to $y/Z (T)$) as suggested by Pagel (1997) is assumed. From the metallicities and the surface density of the stars we construct the relative distribution of stars over their metallicity, which we compare with the empirical distribution obtained by Wyse & Gilmore (1995) using data of G dwarfs from the old thin disk. The G dwarf distribution constrains the free parameters fairly tightly and the best fitting model is shown in Fig. 7. As final step we have calculated the Toomre stability parameters for the stellar and gas disks, respectively. Interestingly, the gas disk appears to have been dynamically unstable in earlier
epochs of the evolution of the Milky Way. This meant dynamical instability for the stellar disk as well and considerable disk heating. Using the criterion of Fuchs & von Linden (1998) one can show that the compound star and gas disks were dynamically unstable until \( t = 6 \) Gyrs \((Q_s = 2, Q_g = 1.4)\). Note that the star formation rate was high enough to keep the stellar disk dynamically active. But even later on spiral activity accompanied by star formation will have been quite high and, taken all together, the transition from instability/near instability may well explain the break in the star formation rate 3 to 4 Gyrs ago. However, as can be seen from the lower left panel of Fig. 7, where we illustrate the disk heating effect due to molecular clouds in comparison with the observed velocity dispersions, even given this dynamical disk heating mechanism, which might have heated the old stars, there is still another disk heating mechanism needed to explain the steep rise of the velocity dispersion of the young stars.

As an aside we note finally that the star formation rate of the model of the evolution of the Milky Way disk described here can be expressed empirically as a Schmidt law, \( \dot{\Sigma}_* \propto \Sigma_g^{1.55} \).

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Discussion

Lynden–Bell: You do not need a refocussing of stars within a stream. There are two diffusions – the first is the diffusion that moves around the streams but are large scale gravity perturbations that leave Liouville’s theorem unchanged so we see the streams intact. The second diffusion is diffusion by small scale gravity fields between the different stars in any one stream. Evidently this is a much smaller diffusion.

Fuchs: That is an interesting suggestion. I should explain that due to the accurate Hipparcos parallaxes we also see fine structure in the velocity distribution of the nearby stars. Besides the well known young moving groups there is also a hint for the old moving group Wolf 630, which does not show up among the young stars. We do not see the old Hercules moving group, because the velocity distribution of the nearby stars is too sparsely populated in that part of velocity space in order to find statistically significant crowding.
Figure 1. Total velocity dispersions of the peculiar velocities of stars in the solar neighbourhood. Circles indicate main sequence stars, squares McCormick stars, and triangles refer to G and K dwarfs with quantitatively measured chromospheric emission fluxes. Cepheids are indicated by an asterisk.
Figure 2. Left panel: Scatter plot of the velocities of the stars from the Edvardsson et al. (1993) sample. The U velocity components point to the galactic center, the V components into the direction of galactic rotation, and the W components toward the galactic pole, respectively. The vertical dotted line indicates the transition from old thin disk to thick disk stars.

Right panel: Velocity dispersions of the stars from the Edvardsson et al. sample (squares) in comparison with the CNS4 data (full dots). From top to bottom the radial and tangential velocity dispersions, the mean rotational velocity (with respect to the Sun), the vertical and total velocity dispersions are shown, respectively. Fits to the velocity dispersion data according to equation (1) are drawn as solid lines, scaling as $\sigma_U : \sigma_V : \sigma_W : \sigma_{\text{tot}} = 3.5 : 1.5 : 1 : 5.5$. The asymptotic drift relation is given by $\Delta V = -8 - 0.01\sigma_U^2$. 
Figure 3. Left panel: Velocity dispersions and rotational lag (with respect to the Sun) of the stars from the Dehnen & Binney (1998) sample as function of the $B - V$ colours of the stars. Radial velocity dispersions are indicated by squares, tangential velocity dispersions by circles, and vertical velocity dispersions by asterisks, respectively. Right panel: CNS4 data.

Figure 4. Total velocity dispersion as function of stellar age according to Binney et al. (2000) (dashed line) in comparison with the solar neighbourhood data (solid line and symbols coded as in Fig. 1).
Figure 5. Cumulative star formation rate traced in the solar neighbourhood by a sample of G and K stars with individually determined ages based on their chromospheric emission fluxes. The rise of the curve from the right to the left indicates the growth of the surface density of the galactic disk during its evolution (see text for details).

Figure 6. Results of the numerical simulation of the effects of the bombardment of the galactic disk with massive cold dark matter clumps from the galactic halo. The left panel shows the resulting mean velocities ($<U>$, $<W>$, $<V>$ from top to bottom over the first 1000 Myrs) and the right panel shows the resulting velocity dispersions ($\sigma_{\text{tot}}$, $\sigma_U$, $\sigma_V$, $\sigma_W$ from top to bottom).
Figure 7. Upper left panel: Surface densities of stars and interstellar gas in the solar neighbourhood extrapolated backwards. Upper right panel: Relative distribution of long-lived stars over their metallicity. The solid line is the model and the dash-dotted line indicates the empirical distribution. Lower left panel: Observed velocity dispersions fitted by a $\tau^{1/2}$ law (solid line) and the disk heating effect due to molecular clouds (dashed line). Lower right panel: Stability parameters of the stellar and gas disk, respectively, extrapolated backwards.