Self-consistent dynamical model of the vertical disk profile in the solar vicinity

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Abstract

The star formation rate history and the dynamical heating of the stellar populations determine the vertical density profile and the age distribution of the disk stars. The local velocity distribution $f(W)$ of the stars is strongly coupled to the density profile. Due to their smaller scale height the relative contribution of young stars is enhanced resulting in stronger signatures of the dynamical evolution of the disk in the shape of $f(W)$.

For different star formation rates SFR and adopted dynamical heating functions we derive self-consistent vertical density profiles including the gravitational potential of the gas component and the metallicity dependent life times of the stars. From a comparison of the local velocity distribution of the stars with observations we find that the density profile shows a central flattening of a factor of 2 compared to an exponential one. This leads to a local total mass density of $0.115 M_\odot/pc^3$ and a surface density of $102 M_\odot/pc^2$ up to 2kpc using a scale height of $250pc$. The DM-Halo with a local density of $0.01 M_\odot/pc^3$ contributes 50% to that surface density. We find also constraints on the overall shape of the SFR.

Introduction

The velocity dispersion of the stars in the solar neighbourhood increases continously with age τ. The observational data can be well fitted by a linear increase of the kinetic energy ($\sigma^2 = \sigma_0^2 + C\tau$) with age (see Fig. 1a). This implies also an increasing thickness $2h(\sigma)$ of the vertical stellar distribution of the subpopulations with age. As a consequence the subpopulations contribute differently to the total density at different heights z above the plane. A discussion of the vertical disk structure of late type galaxies can be found in Just et al. (1996).

In a physical model of the disk the vertical distribution of the stars is mainly determined by the star formation history $SFR(\tau)$ and the dynamical heating function $\sigma(\tau)$. Additionally the gravitational force of the gas component and the DM-halo, and the finite life times of massive stars (which are metallicity dependent) are important. In order to derive the SFR from solar neighbourhood data, the local volume density ρ of stars must be converted to surface densities Σ of the disk. This is very sensitive to the chosen density profile and the total potential, which is not directly observable. The velocity distribution function $f(W)$ of a subsample of stars in the solar neighbourhood gives additional information on the disk structure, because the shape of $f(W)$ depends directly on the gravitational potential $\Phi(z)$. In an earlier paper Fuchs and Wielen (1993) computed $\Phi(z)$ from $f(W)$ of the McCormick K and M dwarfs directly by adopting a correction function on $f(W)$ to get the velocity distribution of the total disk mass. We are going the other way around using $f(W)$ of different stellar subsamples to constrain the disk models (especially the SFR).

Disk models

We construct a self-consistent stellar disk with gas and DM-component to derive density profiles for different populations, the age distribution of the stars, and the velocity distribution $f(W)$ in the solar neighbourhood. The stellar population of the thin disk is decomposed into a sum of isothermal components of different ages with surface density given by the star formation rate SFR. We assume a Scalo IMF and take the metallicity dependent life times of the stars into account. For the metallicity enrichment we use a simple model to fit the observations of Twarog (1980) and Edvardsson et al. (1993) (see Fig. 1b). The velocity dispersion is determined by the heating function, for which we adopt different functions $\sigma(\tau)$ according to the observed kinematical data (see Fig. 1a). The density profile is determined by the self-gravitating potential

$$\Delta\Phi = 4\pi G(\rho_s + \rho_g + \rho_D) \tag{1}$$

and dynamical equilibrium

$$\rho_s = \int \frac{SFR(\tau)}{2h(\sigma)} \exp(-\Phi/\sigma^2(\tau))\mathrm{d}\tau, \tag{2}$$

where the thickness $2h = \Sigma_i/\rho_{i0}$ for each component is implicitely determined by the potential $\Phi(z)$. The potential of the gas and the DM-halo is included, the other components (bulge, thick disk) can be neglected for our purpose. The scale height of the gas is about 1/3 of the stellar scale height.

We compare 4 models with different SFRs (see Fig. 1c) and heating functions (see Fig. 1a). Mass loss due to stellar evolution is not included here resulting in a slight overrepresentation of old populations in the gravitational forces of the stellar component. The shapes of the density profiles show a decreasing central flattening and an increase of the scale height with the age of the subpopulations. Young populations have narrow Gaussian density profiles, whereas the density profiles of old populations are wide and slightly flattened exponentials. For model 2 the profiles of subpopulations with different ages are shown in the lower part of Fig. 1d. The total density profile of the stars is a superposition of

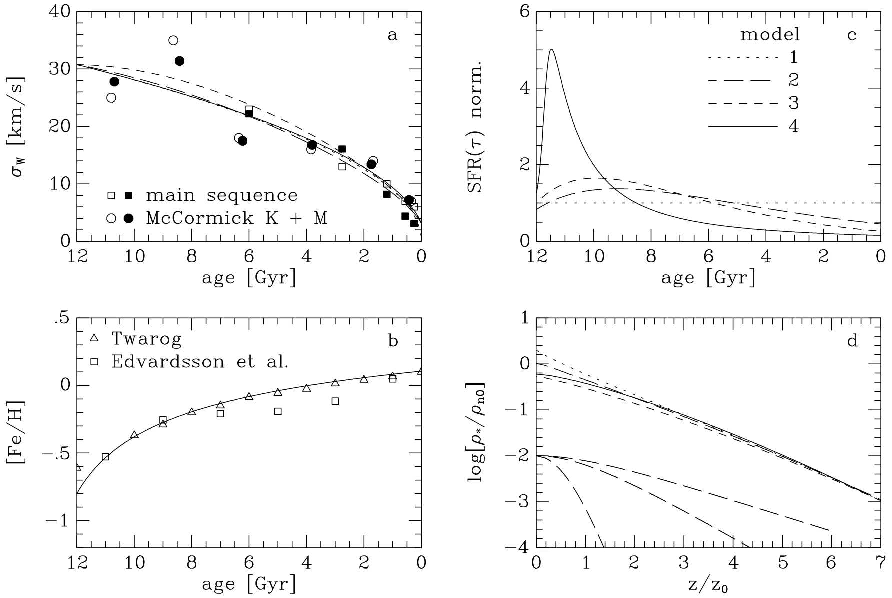

Figure 1: **a:** Dynamical heating in the solar neighbourhood. Data are from the CNS2 (open symbols, Wielen et al. 1992) and from the CNS4 including HIPPARCOS corrections (filled symbols, Jahreiß and Wielen 1997). Heating functions of models 1–4 are shown. **b:** Metallicity measurements from Twarog (1980) and Edvardsson et al. (1993). The full curve shows the metal enrichment used for the determination of the life times in all models. **c:** Star formation histories SFR normalized to a mean of 1 for the different models. **d:** Self-consistent density profiles normalized to the same asymptotic exponential (with scale height z_0) at large heights z. The lower curves show the density profiles of subpopulations of model 2 with ages 1.2, 6, and 10.8 Gyr normalized to a common central value.

components with age dependent effective thicknesses $2h(\sigma(\tau))$. In Fig. 1d it can be seen that the profiles with a large contribution of young stars (model 1) is steeper than exponential at the centre, whereas populations with a small portion of young stars (model 4) have flattened profiles. The large relative difference in central density of a factor of about 3 between model 1 and 4 is reduced to a factor of 2, if the profiles are normalized to an equal surface density.

Velocity distribution functions

The distribution function of the vertical velocity component $f(W)$ is composed of Gaussians weighted by the local number density of the subpopulations of different ages. For the solar neighbourhood ($z=0$) we find

$$f(W)=\int \frac{SFR}{2h}\frac{1}{\sqrt{2\pi\sigma}}\exp(-W^2/2\sigma^2)\mathrm{d}\tau, \tag{3}$$

where SFR, σ, and h depend on the age τ. Low mass stars with life times longer than the adopted age of the disk have the same velocity distribution $f(W)$ as the total stellar mass of the disk, since mass loss due to stellar evolution is neglected here (in a following paper mass loss will be included). A sample of 516 McCormick K and M dwarfs with space velocities is the best one available, because it is large and has no kinematical biases (Jahreiß, these Proc.). In Fig. 2a these data are compared with $f(W)$ of the 4 models described above. Large differences at low velocities can be seen, such that a discrimination between the models is easily possible.

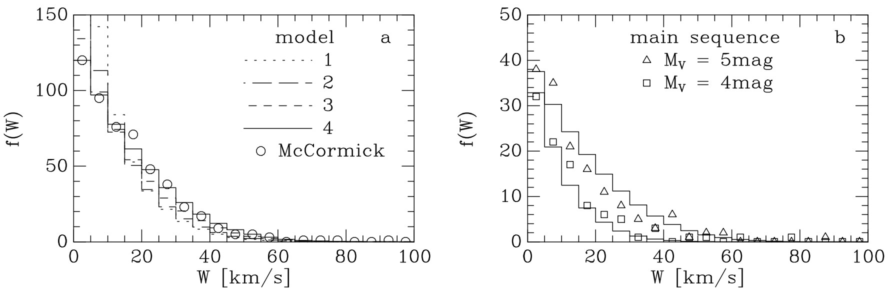

Figure 2: **a:** Velocity distribution function $f(W)$ in the solar vicinity of the models compared to a sample of 516 McCormick K and M dwarfs. **b:** $f(W)$ of model 4 for main sequence stars with life times shorter than the age of the disk and the corresponding samples from the Catalogue of Nearby Stars.

Model 4 is the best fitting model for which we show in Fig. 2b the velocity distributions of more massive main sequence stars with shorter life times. Stars with $M_V=5\pm0.5mag$ and $M_V=4\pm0.5mag$ from the Catalogue of Nearby Stars are plotted. The velocity distribution functions $f(W)$ become more peaked, because the old component with large velocity dispersion has already been died out. The normalization depends strongly on the IMF and will be discussed in a forthcoming paper.

Results

In the previous section we have shown, that model 4 with a star formation time scale of $\approx 4Gyr$ fits with the observed velocity distribution functions. This result depends mainly on the adopted dynamical heating function $\sigma(\tau)$. For a fixed density profile the local density ρ_0 and the total surface density Σ can be determined from the maximal velocity dispersion σ_e and the exponential scale height z_e at large z of the disk via

$$z_e = \frac{\sigma_e^2}{2\pi G\Sigma} \quad \text{and} \quad \Sigma = 2h\rho_0. \tag{4}$$

In an exponential disk z_e equals the observed scale height z_0 and also the thickness h, but for general vertical profiles there are correction factors

$$z_0 = az_e \quad \text{and} \quad h = bz_0 \tag{5}$$

leading to

$$\rho_0 = \frac{a}{b}\frac{\sigma_e^2}{4\pi G z_0^2} \quad \text{and} \quad \Sigma = b2\rho_0 z_0 = a\frac{\sigma_e^2}{2\pi G z_0}. \tag{6}$$

For model 4 we get the correction factors $a = 1.1$ and $b = 1.6$ (in comparison to the exponential model) yielding the correction factor $a/b = 0.69$ for the local density. Using for the solar vicinity $\sigma_e = 25km/s$ and $z_0 = 250pc$ we find for the stellar component

$$\rho_{s0} = 0.04\frac{M_\odot}{pc^3} \quad \text{and} \quad \Sigma_s = 35\frac{M_\odot}{pc^2} \tag{7}$$

consistent with Jahreiß and Wielen (1998). For the gas component we used $\rho_{g0} = 0.06 M_\odot/pc^3$ and $\Sigma_g = 15M_\odot/pc^2$, and for the DM-halo $\rho_{D0} = 0.01M_\odot/pc^3$. This yields a reduced total local density of $\rho_0 = 0.11M_\odot/pc^3$ compared to the Oort limit of $\rho_0 = 0.15M_\odot/pc^3$, although the total surface density up to 2kpc is $\Sigma = 102M_\odot/pc^2$, There is no need of additional dark matter in the disk.

Using a self-gravitating disk model we constructed a consistent vertical density profile (model 4) to reproduce the local velocity distribution functions for different stellar samples. The velocity distribution functions are peaked due to the concentrated young stellar population at the midplane. But the local density is reduced due to the central flattening of the density profile. The corresponding star formation rate is decreasing with a time scale of about 4Gyr.

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