Kinematics of the Galactic populations in the GAIA era

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Abstract.

GAIA data will create a precise 3-dimensional map of the Galaxy, providing positional information, radial velocities, luminosity, temperature and chemical composition of a representative sample of stars. Here we present a new implementation of the Padova Galaxy Model, where kinematics simulations are included. A few examples of application to GAIA science are discussed, in particular concerning radial velocities determinations of the thin and thick disk.

1. Introduction

GAIA will provide detailed phase space coordinates for about 1 billion stars within a sphere of 20 Kpc. In addition to this on board multicolour photometry and spectroscopy will give complete chemical measurements (including α, s, r process elements) down to V=17-19 mag. Owing to the precision of the data, the problem of the formation of the Milky Way will be addressed. In the standard cold dark matter scenario the Galaxy should have formed by mergers of small substructures. However this scenario is at odds with several observational constraints: i.e. a small scale length of the disk of the order of 300 pc is expected instead of 2000-3000 pc (Steinmetz & Navarro 1999); the formation process predicts that the Milky Way should have a thousand of satellites which are missing in the Local Group. A substantial revision of the model is necessary, by means of a detailed comparison with high quality data. GAIA will bring into evidence fossil remnants of the galaxy formation tracing back the star formation history and revealing gradients in the star formation intensity, chemical abundances, and kinematics across the disk. Chemical and age gradients are not expected inside the thin disk. N-body simulations show that radial mixing can wash out gradients close to the Galactic plane after a few Gyr. Concerning the thick disk, if it was formed by an heating event (merge with a satellite) traces of it should still be detectable (Freeman & Hawthorn 2002). In fact vertical gradients in metallicity and velocity dispersions which are still uncertain from the present data are possibly not washed out by the radial mixing far from the Galactic plane and can be used to trace back the formation history. In order to simulate Galactic data we update the Padova Galaxy Model including velocity space and we apply it to the GAIA science.
2. Padova Galaxy Model

The Galaxy is modeled with the code already described by Bertelli et al. (1995) and revised as in Vallenari et al (2000) where more detail can be found. The Padova model has been newly updated including:

1) the usage of new stellar tracks from Z=0.0001 till Z=0.03 with low mass stars down to 0.15 (Girardi et al 2000). 0.1 M⊙ track is taken from Baraffe et al (1998);

2) the use of the carbon star models taking into account the effect of the variation of the stellar molecular opacities during the evolution as a result of the dredge-up (Marigo 2002);

3) the extinction along the line of sight derived following Drimmel & Spergel (2001) model obtained from COBE-DIRBE infrared data.

4) the velocity space simulated in a consistent way as described in the following Section.

3. The kinematic model

The velocity distribution for the whole disk has been computed using the velocity ellipsoids formulation by Schwarzschild. Concerning the thin disk, the assumed local values of velocity dispersions are taken as in Mendez et al (2000). The \( V_{lag} \) is derived following Binney & Tremaine (1994). The diagonal terms of the dispersion velocity tensor are from Lewis & Freeman (1989):

\[
\sigma_{RR}^2 = \sigma_{RR,0}^2 \exp(-(R-R_0)/H_R) \\
\sigma_{\Phi\Phi}^2 = \frac{1}{2}(1 + (d\ln V_{LSR}(R))/(d\ln R)) \times \sigma_{RR}^2 \\
\sigma_{ZZ}^2 = \sigma_{ZZ,0}^2 \exp(-(R-R_0)/H_R)
\]

The vertical gradient in the velocity dispersions is taken from Fuchs & Wielen (1987) for \( \sigma_{RR}^2 \) and \( \sigma_{\Phi\Phi}^2 \) and the non vertical isothermality of the thin disk from Amendt & Cutterford (1991) which is in good agreement with the observations till 1 Kpc for \( \sigma_{ZZ}^2 \). The off diagonal term \( \sigma_{RZ} \) is derived from Amend & Cutterford (1991):

\[
\sigma_{RZ}(R, Z) = \sigma_{RZ}(R, 0) + z\partial/\partial z \sigma_{R,Z}(R, 0)
\]

where

\[
\partial/\partial z \sigma_{RZ}(R, 0) = \lambda(R)(\sigma_{RR}^2 - \sigma_{ZZ}^2/R)(R, 0)
\]

and

\[
\lambda(R) = (R^2 \Phi_{Rzz}+3\Phi_R + R\Phi_{RR} - 4R\Phi_{ZZ})(R, 0)
\]

where \( \Phi_{Rzz}, \Phi_{RR}, \Phi_{ZZ} \) are the derivatives of the Galactic potential \( \Phi \) obtained from the density model by Dehnen & Binney (1998) by inverting the Poisson equation with the Bessel integrals (Quinn & Goodman 1986). \( \lambda \) is an approximate expression of the vertical tilt of the velocity ellipsoid close to the
Galactic plane (at z=0). $\lambda$ is 1 in the case of a spherical potential, when the ellipsoid is pointing towards the Galactic center, while $\lambda$ is 0 for a cylindrical potential when the ellipsoid is always parallel to the Galactic plane. Amendt & Cutterford (1991) show that $\lambda$ is related to the mass gradient in the Galactic plane. No vertex deviation is included in the model although a deviation decreasing from 25° for young stars to near zero for an old population has been found by various authors (Dehnen & Binney 1998, Bienayme 1999, Soubiran et al 2002). The thick disk is isothermal with $(\sigma_{RR}, \sigma_{\Phi\Phi}, \sigma_{zz}) = (70, 50, 45)$ Km s$^{-1}$ as starting values. The $V_{lag}$ is assumed to have a canonical value of 35 Km s$^{-1}$. The possibility of simulating a vertical gradient in the rotational velocity of the thick disk is included as suggested by Chiba & Beers (2000). The halo has $(\sigma_{RR}, \sigma_{\Phi\Phi}, \sigma_{zz}) = (130, 95, 95)$ Km s$^{-1}$. The projection matrixes of the space velocities are derived from Mendez et al (2000). In the following Sections we show a few examples of applications to the GAIA science. In particular the thin and thick disk are discussed.

4. Disentangling various stellar populations

Spectrograph aboard on GAIA operating in the near-IR will measure radial velocities with an accuracy better than 2 Km s$^{-1}$ if an high dispersion of 0.25 A$^2$/pix is chosen for stars brighter than V= 16 mag. The expected accuracy will still be better than 8 Km s$^{-1}$ for magnitudes as faint as V=17, but will drop to 30 Km s$^{-1}$ at V=18 (Zwitter 2002) for a G2V stars. This amount of unprecedented good quality data will allow to disentangle thin disk, thick disk and halo populations, deriving ages, metal content and kinematics. Fig. 1 presents a simulation of the expected radial velocities at (l,b)=(270,-45) for a 2.5 $\times$ 2.5 deg$^2$ field for stars brighter than V=17, 17.5, and in the magnitude range 17.5-18 at an heliocentric distance of 2000-4000 pc where the contribution of the thick disk is relevant. Expected observational uncertainties are included. The thick disk population begins to contribute significantly at magnitudes fainter than V=17. In order to disentangle thin and thick disk populations, a fainter magnitude limit would be more effective, unless kinematic information is coupled with chemical abundances determinations.

5. The thick disk velocity gradient

The presence of a gradient in the thick disk velocity dispersion or a multi-component structure is indicative of the formation process as described in Section 1. From the observational point of view the situation is far from being clear. Soubiran et al (2002) find a thick disk with a moderate rotational and vertical kinematics, but no vertical gradient suggesting a quick heating of the precursor thin disk. Chiba & Beers (2000) suggest that far from the plane the thick disk has lower rotational velocity and higher velocity dispersion than close to the Galactic plane. These data are interpreted as a vertical gradient of about 30 Km/s/Kpc. Gilmore et al (2002) propose a different interpretation of the data: the thick disk has a composite form, indicating the presence of relics of disrupted satellites. Fig. 2 shows a simulation of the thick disk population in a column of 0.09$\times$ 0.09 deg$^2$ at (l,b)=(270,-45) for stars brighter than V=17.5.
Even including the expected GAIA accuracy for an intermediate dispersion of 0.5 A°/pix, still the effect of a vertical gradient of 10 Km/s/Kpc is visible.

6. The vertical tilt of the thin disk velocity ellipsoid

Up to now the vertical tilt parameter $\lambda(R)$ of the thin disk velocity ellipsoids is ill-determined. $\lambda$ is in fact strongly related to the coupling of the U and W velocities and is better constrained by 3-dimensional velocities. It is found to vary from 0.4 to 0.6 at the solar circle (Amendt & Cutterford 1991, Bienaymé 1999). Fig. 3 shows the expected proper motions and radial velocities of the thin disk population under different assumptions for $\lambda(R)$, namely 0, 1 and following Amendt & Cutterford (1991) in the direction (l,b)=(26,6). The simulations take into account the uncertainties on GAIA determinations for stars brighter than $V=17$. In comparison to the models having $\lambda(R) = 0$ or 1, the model with $\lambda(R)$ related to the potential predicts differences of the mean value of the radial velocities going from 5 to 15 Km/s, depending on the distance. On the proper motion $\mu_l$ the effect is at maximum 0.2-0.4 mas/yr, while it is definitely less than 0.08 mas/yr on $\mu_b$. GAIA expected precision on radial velocities and proper motions will be able to put strong constraints on the determination of the tilt of the velocity ellipsoid.

7. Conclusions

GAIA data will create a precise 3-dimensional map of the Galaxy, providing positional information, radial velocities, luminosity, temperature and chemical composition of a representative sample of stars. Here we present a new implementation of the Padova Galaxy Model, where kinematics simulations are included. This model includes a description of the vertical tilt of the ellipsoids
Figure 2. The effect of the thick disk velocity gradient. Dashed line shows a model with no vertical gradient; heavy solid line presents a vertical gradient of 10 Km/s/Kpc, thin solid line is the analogous for a vertical gradient of 30 Km/s/Kpc. $d$ is the heliocentric distance.

Figure 3. The differences of the mean values of $V_{rad}$ and $\mu$ at varying $\lambda(R)$ are plotted as functions of the Galactic radius $R$ for magnitudes brighter than $V=17$. Dotted lines show the difference between the models using $\lambda = 0$ and 1; the dashed-dotted lines are the analogous for $\lambda = \lambda(R, \Phi)$ and 0; and finally the dashed-dotted lines are the analogous for $\lambda = 1, \lambda(R, \Phi)$. 

of the velocity of the thin disk following Amendt & Cutterford (1991), in addition to isothermal thick disk and halo. This formulation might be specially useful to simulate the kinematics of the thin disk till a vertical height of 1 Kpc. A few examples of application to the GAIA science are presented, in particular concerning radial velocities determinations. The main conclusions are:

1) the expected accuracy on radial velocities will put strong constraints on the determination of the vertical tilt of the velocity ellipsoids of the thin disk;

2) since the thick disk begins to contribute significantly at magnitudes fainter than V=17, to disentangle thin and thick disk populations at high latitude, a fainter magnitude limit would be more effective, unless kinematic information are coupled with chemical abundances determinations;

3) finally, the expected accuracy on radial velocities at intermediate dispersion will allow the determination of a possible vertical velocity gradient in the thick disk of at least 10 Km s$^{-1}$.

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