KINEMATICS AND THE GALACTIC POTENTIAL

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1. Introduction

The analysis of stellar kinematics and the Galactic potential is linked to the study of the spatial distribution of stars in the Galaxy since they are related through the Boltzmann and Poisson equations. Measuring all the visible density and mass distribution from general star counts and the gas cloud density gives only a small fraction of the total amount of the dynamical mass that is deduced from the kinematics of the galactic constituents. As in many spiral galaxies, most of the Galactic mass is unseen and unknown.

We could classify the main potential, or mass, "tracers" as 1) those related to the determination of the rotation curve : HI and CO clouds, young disc populations like Cepheids or young open clusters; 2) those related to the study of the density distribution perpendicular to the galactic plane and the determination of the plane galactic density: gas flaring and stellar samples up to 1 or 2 kpc towards the Galactic poles; 3) samples related to a 3D halo analysis, such as RR Lyrae or BHB stars, globular clusters and at larger distances galactic satellites (see reviews by Fich & Tremaine 1991 and Crézé 1991).

It is important to find tracers corresponding to the very different scales in order to obtain an accurate determination of the potential at each scale. This will help to clarify some unsolved questions: what is the exact mass density at large galactic radius; what is the shape of the dark matter distribution—spherical dark halo or flat; is it triaxial; is there a stellar population with intermediate angular momentum? In particular, many observational efforts linking deep star counts to radial velocities and proper motions measurements are still needed.

Another essential question is to determine the evolutionary relationship between stellar populations in the different components of the Galaxy.

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Links between kinematics, stellar ages and chemical abundances allow one to build the dynamical history of the Galaxy from the old, metal-poor stars of the stellar halo to the present, young disc stars (Gilmore *et al.* 1989). Such studies provide the opportunity to understand the formation, evolution and structures of galaxies in general and to discriminate between formation scenarios: 1) Halo stars formed during a free-fall collapse of the proto-Galaxy and disc stars formed later with enriched gas in a rapidly rotating disc (Eggen *et al.*1962); 2) An alternative model is that the halo formed as a merger of dwarf galaxies over several Gyr (Searle & Zinn 1978). Reality looks certainly much more like a combination of these two scenarios.

2. The Galactic Disc

2.1. THE ROTATION CURVE

Gas clouds (HI and CO) move on nearly closed and circular orbits in the galactic plane around the galactic centre, and it is possible to recover their rotational velocity as a function of galactic radius at least up to the solar galactic radius, R_0. Distances of gas clouds are not known, but the tangent point method allows one to build the rotation curve (RC). The exact shape of the RC depends on both R_0 and V_0 (circular velocity at R_0) which are not yet determined with sufficient accuracy to know, for example, if the RC is locally rising or decreasing. The asymmetry in the observed gas velocity field between positive and negative galactic longitudes shows evidence for the presence of a barred potential, at least in the inner part of the Galaxy. Evidence for this bar (de Vaucouleurs & Pence 1978) also come from IR observations (Dwek *et al.* 1995, see also a recent review by Weinberg 1996). Outside the solar galactic radius, young objects (Cepheids...) on nearly closed orbits with measurable distances allow one to determine the RC up to $R \simeq$ 15 kpc (Fich & Tremaine 1991).

The potential can be recovered from the rotation curve assuming the shape of the mass distribution (spherical, flat). The rotation curve at a given radius constrains mainly the amount of mass inside this radius. Forces from dark matter contribute for half to the RC at the solar radius. This estimate depends on the mass assigned to the stellar disc and its scale length.

2.2. STELLAR THIN DISC

According to external spiral galaxies, stellar discs are exponential. The Galactic thin disc is a continuum of discs with varying age, metallicity, kinematics and morphology. Scale-heights range from 75 pc to 250 pc, and

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vertical velocity dispersions from 5 to 20 km s^{-1}. Most recent scale length determinations favour short values ~ 2.5 kpc (Robin *et al.* 1992).

It is very difficult to find evidence from star counts in the galactic plane for ellipticity of the stellar disc at the solar galactic radius, particularly if we are on one of the symmetry axes. Signatures from kinematics give more reliable constraints (Kuijken & Tremaine 1994): Oort's constants C and K, the LSR radial velocity, show no evidence for non-axisymmetry, while vertex deviation (velocity ellipsoid not pointing towards the galactic centre) may show such evidence. However, this effect could be caused by very local non-stationary effects related to the presence of spiral arms. Likewise the axis ratio σ_u/σ_v is observed to be about ~ 0.5 and can be a signature of ellipticity (Kuijken & Tremaine 1994), but may also be simply explained if the rotation curve is locally slightly decreasing, or if the kinematic and density scale lengths are very different (Bienaymé & Séchaud 1996). More complete and detailed analysis will be possible with the extended sample given by Hipparcos.

A global analysis of the stellar discs is possible with OH/IR stars and Planetary Nebulae that can be identified near the plane at large distance and for which radio observations supply accurate radial velocities. Such data give a unique opportunity to measure stellar density, orbital structure and kinematic gradients over large areas of the Galactic disc (te Lintel Hekkert 1990; Sevenster *et al.* 1995; Durand *et al.* 1996). Systematic searchs closer to the Galactic plane are possible (Kistiakowsky 1995) and are promising for the study of younger populations and kinematic-gradient.

2.3. K_Z FORCE PERPENDICULAR TO THE GALACTIC PLANE

Comparing scale heights of stellar discs to the vertical velocity dispersions σ_w of their constituents gives direct access to the vertical potential. In the academic case of a stellar sample distribution $\rho_*(z)$ where σ_w does not vary with height and when distances are below 1 kpc, we have $\Phi(z) = \sigma_w^2 \log(\rho_*(z)/\rho_*(0))$. Then the local dynamical mass ρ_{dyn} may be easily deduced from the potential. There has been a long controversy as to whether the dynamical mass is in excess of the total "observed" mass density ($0.09\, M_\odot \mathrm{pc}^{-3}$), the main discussion being concerned with the quality of used samples. A summary of the most recent results are given by Crézé (1991) and Kuijken (1995) where it appears that the most accurate samples indicate no need for a flat disc of dark matter. Though less constraining, vertical HI gas dynamics favour this conclusion (Boulares & Cox 1990; Malhotra 1995).

2.4. THICK DISC

The thick disc (TD) is identified by star counts at high galactic latitude (Reid & Majewski 1993) and also by distinctive kinematic signatures that are constant at various heights above the galactic plane (Soubiran 1993; Ojha *et al.* 1994ab). The TD has a large rotational velocity, looking more like the thin disc populations than those of the halo, but its kinematics remain fully separate from the disc. This is very probably the signature of a merging event in the early phase of the Galactic disc's formation (Robin *et al.* 1996; Ojha *et al.* 1996). This may explain also the absence of a vertical abundance-gradient (Gilmore *et al.* 1996).

The thick disc vertical velocity dispersion ($38\,\mathrm{km\,s^{-1}}$, Beers *et al.*1996) and scale height (750 pc, Robin *et al.* 1996; Ojha *et al.*1996) can be used to estimate the K_z force at large z (1–2 kpc). We estimate that it is consistent with no massive disc of dark matter (the plane-parallel approximation is no more valid so far from the plane and a complete 3D modeling would be necessary).

3. The Galactic Halo

Understanding and modeling the 3-dimensional dynamics of halo stars has progressed rapidly during the last few years; see, for example, models like the Stäckel potential with three explicit integrals of motion or models with action integrals (Dehnen & Binney 1996) or with orbit computations (Flynn *et al.* 1996).

The quantity of available kinematic data for distant halo stars is surprisingly low, and most of our knowledge is based on local kinematics.

Halo samples with 3-D kinematics seem to show substructures that could be fragments of destroyed globular clusters or else... (Majewki *et al.*1996). In fact, the mixing time for halo stars is a few Giga-years and relaxation is not fully achieved (Tremaine 1993). We expect partial mixing to leave traces of initial formation or accretion period. Non-stationarity will limit the description of the Galactic potential, but it is also a unique chance to find explicit and "still" living traces of Galactic formation.

3.1. NON-LOCAL HALO TRACERS

The stellar halo density distribution is adequately modeled by a power law spheroidal distribution with flattening given by an axis ratio of about $c/a = 0.5$–0.7 (Larsen & Humpreys 1994).

The accuracy of halo density distribution based on medium deep star counts of subdwarfs is limited by the thick disc (intermediate component) that must be subtracted accurately. Halo star identification is much easier by combining counts and proper motions, since the quasi null-rotation of the halo is easily identifiable (Soubiran 1993).

Specific tracers, such as RR Lyrae or BHB (Layden 1995; Kinman 1994) allow one to identify the density and kinematics of different halo sub-components. Carney *et al.* (1994) obtained an important local kinematic halo sample, and Beers *et al.* (1996) build a non-kinematically biased sample of 1936 nearly local halo stars with low metallicity. Such samples allow one to determine the halo and thick disk local kinematic properties.

For distant stars, radial velocities are known in a dozen Galactic directions, with a few tens of stars in each direction. Modeling the observed radial velocity distribution of RR Lyrae or BHB (Arnold, 1990; Flynn *et al.* 1996; Sommer-Larsen *et al.* 1994) with different anisotropic velocity distributions allows one to deduce the possible distribution functions (DF) and to deduce limits on realistic potentials. Most of these stars are distant and their tangential velocity is unknown, so models with different tangential velocities and very different potentials are found to be equally probable. Without accurate proper motions, just a lower limit is obtained on the total Galactic mass distribution.

Globular clusters (GC) are important halo tracers at large distances giving information on the potential up to 40 kpc (Dauphole & Colin 1995; Kochanek 1996). GC samples are probably not complete (Da Costa 1995), detection biases are unknown, and there is a lack of reliable proper-motions for the more distant GC. These two elements prevent an accurate definition of the potential up to 40 kpc, but are compatible with a flat or rising rotation curve up to that radius.

A similar analysis based on satellites of the Galaxy allows one to explore the potential further away. The analysis is based on a small number (25) of objects with only 3 measured and usable proper-motions (Kochanek 1996). The assumption of stationarity is certainly doubtful due to typical crossing time of orbits.

Metal-poor Blue Main sequence Stars near the solar circle have been discovered by Preston *et al.* (1994) as a new kinematic population. These stars have an isotropic velocity dispersion and relatively large mean rotational velocities of about 128 km s^{-1}. Preston *et al.* suggest they are probably accreted from dwarf spheroidal satellites. It will be essential to extend the detection of this population out the galactic plane, since it will be the best potential tracer at intermediate distances around 3–6 kpc out of the Galactic plane.

3.2. LOCAL TRACER : ESCAPE VELOCITY

A classic method (for example : Carney *et al.* 1988; Kochanek 1996) for probing the Galactic potential at very large radius consists of determining the local escape velocity from the velocity distribution of high velocity stars. In the solar neighbourhood, it is estimated to be between 450 and $650\,\mathrm{km\,s^{-1}}$. If stars with larger velocities evaporate and leave the Galaxy, we get a lower limit to the total mass of the Galaxy. The observed escape velocity implies a galactic total radius $R_{lim} \geq 34\,\mathrm{kpc}$ for a flat rotation curve up to R_{lim} and no mass beyond that radius (Cudworth 1990). This approach suffers from various difficulties. Firstly, large velocities stars are selected from large proper motion surveys and are biased towards objects with the largest proper motion errors, although in principle this can be corrected. Secondly, it is not excluded that these large velocity stars are visiting evaporated stars from a satellite of the Galaxy, like the Magellanic Clouds or a neighbouring dwarfs galaxy.

3.3. LOCAL TRACER : POTENTIAL FLATTENING

The velocity distribution of local stars is not only a mixture of the history of various stellar populations, but also reflects the potential. This may be shown, for example, at $z = 0$ for a spherical potential and a flat rotation curve ($=v_c$). In this case, the DF may be written as:

$$f(r, z = 0; v_r, v_\theta, v_z) = e^{-\frac{v_r^2}{2\sigma_r^2}} * e^{-\frac{v_z^2}{2\sigma_z^2}} * e^{-\frac{v_z^2}{2\sigma_z^2}(\frac{v_c^2}{v_\theta^2}-1)(\frac{\sigma_z^2}{\sigma_r^2}-1)} * fct(r, v_\theta)$$

The correlation between vertical the v_z and tangential v_θ velocities is non-existent for a plane-parallel potential. This correlation term is important for disk populations with large velocity dispersions. Analysing the Gliese catalogue of nearby stars, we estimate that the flattening of the potential is $\sim 0.6 \pm 0.4$ (Pichon & Bienaymé 1996). Analysing a larger local sample will allow one to evaluate the potential flattening with a better accuracy.

3.4. VELOCITY ELLIPSOID INCLINATION : POTENTIAL FLATTENING

Exact dynamical modeling of halo tracers requires complete 3D models. However, correlations between radial and vertical motions may be just obtained from the orientation of the velocity ellipsoid, and probe the shape of the potential without need for accurate measurements of the density distribution. In the case of a Stäckel potential, this orientation does not depend on the velocity dispersion. In a spherical potential, the ellipsoid points towards the Galactic centre while in a plane-parallel potential it stays parallel to the Galactic plane.

The Majewski *et al.* (1996) sample at large distances above the Galactic plane can be examined with this purpose, although they remark that it shows substructures and is probably not kinematically mixed. Features in their (u,w) velocity plot (Figure 2) may reflect initial conditions. However, if the star groups came from an initial cluster with very small internal dispersion, the resulting structure observed today, and partially mixed in the halo, will plot such a (u,w) diagram and will just trace an iso-potential pointing towards ($R = -5$ kpc, z=0) beyond the galactic center (if $< z >= 5\,kpc$ is the mean distance of these stars). This shows that the potential is oblate and can be reproduced with a nearly spherical dark matter distribution. Thick disc stars should also be good potential tracers at heights 2 to 5 kpc above the galactic plane. However, their ellipsoid inclination will be smaller.

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