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PREPARING THE MODELLING OF GAIA PRODUCTS FOR GALACTIC STRUCTURE AND DYNAMICS WITH MOCK DATASETS

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Abstract. A series of workshops – the 'Gaia Challenge' – has been initiated in 2013 to prepare the scientific exploitation of Gaia data. The first position and velocity observables from Gaia will be released early in 2017. Within this context, I present results from numerical tools developed to constrain Galactic structural and dynamical properties from pseudo Gaia observables (mock data).

Keywords: Galaxy, Milky Way, Structure, Dynamics, Gaia, stars, pattern speed, mass model

1 The Gaia Challenge: preparing the exploitation of Gaia

The European Space Agency Gaia mission* is currently scanning the whole sky. It has been designed to constrain the 2×3D position and velocity space of the Milky Way from an astrometric and photometric survey of about $\sim 10^9$ stars, complemented with a spectroscopic survey of $\sim 10^8$ stars. The Gaia Challenge† collaboration has been recently initiated to prepare the scientific exploitation of Gaia data. Its aim is to develop, improve and apply various techniques to mock Gaia data in order to recover important physical quantities of the Galaxy, like its gravitational potential and the phase-space structure of stars. It is organized around five working groups: 'Streams & Halo Stars', 'Collisional Systems', 'Discs', 'Spherical & Triaxial', and 'Astrophysical Parameters' of stars. The mock Gaia observables come from N-body simulations.

I present here two preliminary results from the numerical tools I have developed for Galactic structure and dynamics, within the framework of the Discs working group. The pseudo-observational Gaia dataset necessary to develop these tools have been obtained from N-body simulations of Hunt & Kawata (2013) and Hunt et al. (2013).

2 Pattern speeds of the Galactic bar and spiral density waves

The pattern speeds (Ω_p) of bars and spirals are fundamental parameters in galactic dynamics. They are needed to determine the orbital structure of dynamical tracers (stars, gas clouds) in discs, and the location of resonances with the disc itself, which in return are essential to understand the structure of discs. One of the many issues for the analysis of Gaia data will be to derive Ω_p of the Galactic bar and other density waves.

Several methods have been proposed by Gaia challengers. For instance, Monari et al. (2013) analyze the U, V velocity space at different Galactic radii and in the Solar neighbourhood to infer the location of the Outer Lindblad Resonance of the bar. Then, the corotation radius and Ω_p can be deduced once a Galactic rotation curve is known. For this challenge, I propose to apply the Tremaine-Weinberg method (Tremaine & Weinberg 1984, hereafter TW). Only Debattista et al. (2002) investigated the possibility to use the radio emission from OH/IR stars to constrain Milky Way pattern speeds by the TW method. However the method has been applied almost exclusively to other galaxies. In particular, it has allowed to show how stellar bars preferentially rotate

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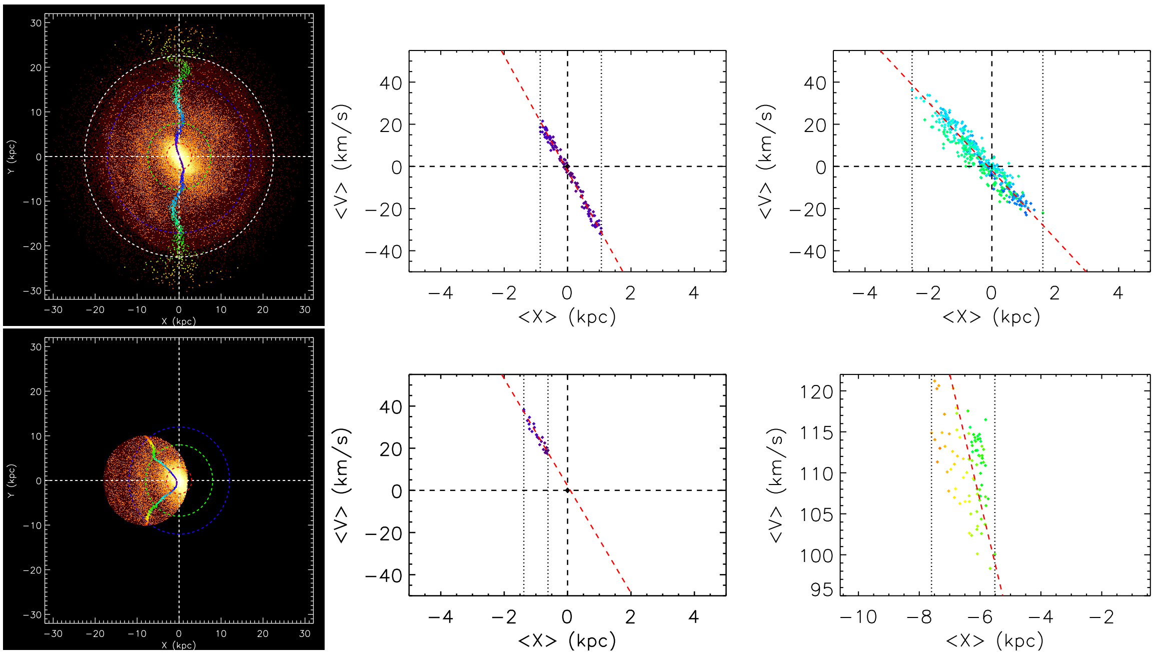

Fig. 1. Derivation of Galactic pattern speeds from mock Gaia data, with the Tremaine-Weinberg method. The top panels are results for the reference full simulation, the bottom panel for the limited volume 'Gaia' dataset. The reconstructed stellar surface density map is shown in the left-hand column, Eq. 2.1 for the bar pattern speed in the middle column, and for the inner spiral pattern speed in the right-hand column. Linear fits to the relationships are the dashed lines, and the colour code simply marks the $y-$coordinate of each point. Dashed circles mark the radii that identify the regions needed for linear fits of the bar and spiral arms pattern speeds.

fastly in early-type discs, while more dark matter dominated discs tend to have slower bars (Corsini 2011, and references therein).

Assuming that the observed kinematical tracer satisfies the continuity equation, and that the target density wave has a well defined pattern angular speed, the method stipulates that integrals of velocities with respect to position are linked with Ω_p and integrals of position with respect to position. From a Galactic viewpoint, the TW method writes in Cartesian coordinates:

$$\int_{-\infty}^{\infty} \Sigma(x,y,t)\ v_y(x,y,t)\ dx = \Omega_p \int_{-\infty}^{\infty} \Sigma(x,y,t)\ x\ dx \tag{2.1}$$

where Σ is the mass surface density of the tracer, and v_y the $y-$component of its velocity vector which is related to the U, V Galactic velocity components and the azimuthal angle θ by $v_y = V\cos(\theta) + U\sin(\theta)$. Since the $x-$ and v_y-integrals vary as y varies due to variation in surface density and velocities, the pattern speed is the slope of Eq. 2.1 in the $< x >, < v_y >$ parameter space.

I have used the barred+spiral disc simulations by Hunt et al. (2013) as provisional mock data. The Navarro-Frenk-White dark matter halo contribution has a virial mass of $M_{200} = 2\ 10^{12}\ M_\odot$, and a halo concentration of $c = 9$ in the initial simulations. The mock Gaia data consist in equatorial positions, parallaxes, proper motions, radial velocities and Gaia magnitudes, which have been converted to the Galactic rest frame using $x, y, z = -8, 0, 0$ kpc and $U, V, W = 0, 228, 0$ km s^{-1} as Sun parameters. Each particle can be considered as a group of a few thousand red clump stars. Surface density maps and velocity fields have first been built. I have considered all 'stars' within $|z| = 1$ kpc from the equatorial plane. To demonstrate the feasibility of the method with the most accurate distances, all stars distant by more than 10 kpc from the Sun position have been discarded from the mock data. This limited Gaia-observable volume is indeed the expected one where Gaia distance accuracy will be $\leq$10% for bright stars. For sake of comparison, the TW method is also applied to the whole mock disc data, again with the only $|z| \leq 1$ kpc constraint (top panels of Fig. 1). Then, integrals of Eq. 2.1 have been calculated for about 1300 $y-$ wedges parallel to the $y = 0$ axis, separated by Δy =50 pc. The derived $x-$integrals of the right-member in Eq. 2.1 are shown as coloured dots in Fig. 1. The colour code

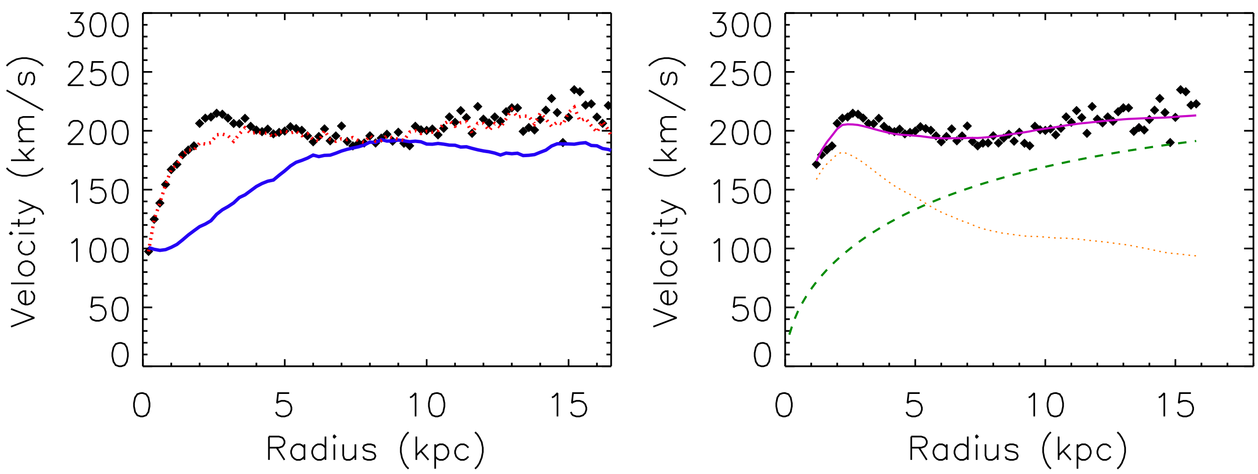

Fig. 2. Left: Derived rotation curve with and without asymmetric drift correction (filled diamonds and blue solid line, respectively) from the mock Gaia data. The mock data are based on N-body simulations of Hunt et al. (2013). The red dotted line is the rotation curve from the reference full volume mock dataset. **Right:** Mass distribution model of the rotation curve. A solid line represents the total mass model, a dotted line the stellar disc contribution, a dashed line the dark matter halo contribution (Navarro-Frenk-White model).

from blue to red colours is for increasing values of $|y|$. Then, the regions where the $x-$locations significantly deviate from $x = 0$ and where the v_y-integral converge have been isolated to identify the regions of the stellar bar and spiral arms, and linear fits to the $< x >, < v_y >$ relationship yield the slope of Eq. 2.1 for each of these regions.

With the reference full simulated volume, it is found a bar pattern speed $\Omega_p = 27$ km s^{-1} kpc^{-1}, and two inner and outer spiral patterns of angular speed of 16 and 9 km s^{-1} kpc^{-1}, respectively. The isolated data corresponding to the bar and inner spiral patterns are shown in middle and right panels of Fig. 1.

The shape of the integrals are different for the limited Gaia-like volume. Here, the opposite disc half to the Sun with respect to the Galactic Centre cannot be observed. As a consequence, the bar region at $y < 0$ is not seen in the density map, and all the positive $x-$integrals seen in the upper panels have naturally disappeared. The $x-$integrals quickly converge towards the location of the spiral structure, as this latter rapidly dominates the stellar mass density for $x, y < 0$. Then, once bar and spiral points have been isolated, it is found $\Omega_p = 25$ km s^{-1} kpc^{-1} for the bar, and $\Omega_p = 16$ km s^{-1} kpc^{-1} for the inner spiral arm. No outer arm is seen in the limited volume. Both values remain in agreement with the whole mock data, though the bar pattern speed is slightly smaller. This latter result is expected because integrals are performed within $[-\infty, \infty]$, and the $x-$integrals in the bar region have become contaminated by the slower spiral structure. The 'loss' of bar surface density is made at the benefits of the 'gain' of spiral surface density. I expect that a radially dependent TW method would avoid that minor artefact. This will constitute future improvements for this work. Another improvement will be for instance to develop a derivation tool based on a two-dimensional reference grid. This should significantly improve the estimate of the bar pattern speed.

3 Mass distribution modelling

More important objectives of the Gaia mission will be to determine the structure and the mass distribution of the Milky Way Disc from the 2×3D position and velocity space. Promising methods for dynamical modelling are e.g. action-based distribution functions (e.g. Bovy & Rix 2013) or made-to-measure models (e.g. Hunt & Kawata 2013). I am developing tools that build stellar density map(s), the Galactic U, V, W velocity fields, derive Galactic structural parameters (e.g. disc scalelength and scaleheight), velocity dispersion profiles and rotation curve, the asymmetric drift correction, and fit mass distribution models using a library of dark matter halo models.

Figures 2 and 3 present some of the provisional results obtained using a mock Gaia dataset based on simulations of Hunt et al. (2013). Results are for the same volume limited mock dataset as in §2 and Fig. 1.

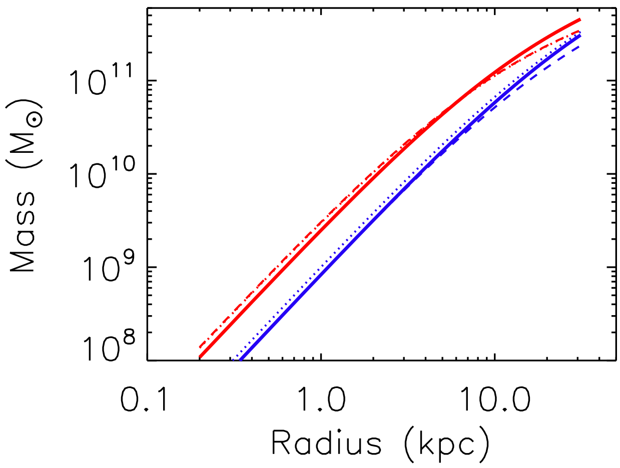

Fig. 3. Input and fitted mass profiles of the dark matter halo. Blue lines are for bar+spiral mock Gaia data (red lines for another type of mock data not discussed in the text). A solid line corresponds to the input Navarro-Frenk-White dark matter contribution in the simulations of Hunt et al. (2013), a dashed line to the fitted mass profile to the full mock volume, and a dotted line to fitted mass profile fitted to the volume-limited mock data.

The average radial force and azimuthal velocity curve profiles are derived (solid line in Fig. 2), to which is quadratically subtracted the asymmetric drift to yield the rotation curve (filled symbols). The rotation curve expected from the full reference mock volume is the dotted line. It is interesting to note that the shape of the rotation curve from the limited mock volume differs by ~ 20 km s^{-1} from the one in the whole mock volume, for $R = 1.5 - 3$ kpc. This is caused by the asymmetric stellar density and velocity distributions within the bar region. Within the whole mock volume, density and kinematical asymmetries are more efficiently averaged (all azimuthal angles are used), while the volume-limited mock data automatically enhance stellar asymmetries (azimuth is only partially covered by selection effects).

Mass models have then been fitted to the rotation curve using the surface density profile of the stellar disc and a Navarro-Frank-White dark matter halo model. The inferred mass profile is shown in Fig. 3 (blue dotted line). The difference with the input NFW mass model of Hunt et al. (2013) (solid line) is negligible, even with the volume-limited mock dataset. The estimated dark matter parameters are $M_{200} = 1.95\ 10^{12}\ M_\odot$ and $c = 10.4$, whose parameters are indeed in excellent agreement with the input halo contribution in Hunt et al. (2013).

4 Conclusions

The development of numerical tools to prepare the scientific exploitation of Gaia products is ongoing. Provisional results show that the derivation of fundamental dynamical parameters is still possible using a limited volume of mock Gaia astrometric and kinematical data from numerical simulations.

It is however important to note that the credibility of these modelling tools is tightly linked to the ability of simulations to mimic realistic pseudo-Gaia products for tens of millions of particles. For now, I have only worked with ideal cases from the initial simulations by Gaia Challenge' numericians. The selection function is quite arbitrary to mimic a limited volume, since particles represent a single stellar population, and neither interstellar extinction laws as function of location in the disc nor the Gaia data error model have been used. In a near future, thanks to the improvement of the numerical simulations, it is envisaged to study the impact of such selection and systematic effects.

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