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Gaia capabilities to determine the length and angle of the Galactic bar

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Abstract

We use a test particle simulation evolved under a 3D potential that includes a Galactic bar to analyse the Gaia capabilities to determine the length and the angle of the Galactic bar. Using the pre-commissioning Gaia science performance models, we generate two realistic mock catalogues of Red Clump K giants. The first includes all stars up to Gaia magnitude, G, 20. The second requires good radial velocities from the Gaia RVS, so we allow a specific maximum error in radial velocity. Once the data from the commissioning phase have been analysed, we will be able to update the performance models and to generate and analyse new catalogues using more realistic input. For the catalogues available at the moment, we plot, for the first time, the stellar surface density in the space of Gaia observables (parallax, galactic longitude). In this space we study the Gaia capabilities to recover the bar characteristics imposed in the analytical potential. If we combine the Gaia data with photometric IR distances, we can recover the bar length and the angle with respect to the Sun - Galactic Centre line.

1 Introduction

Mock catalogues have become very useful in order to be ready to exploit the future large surveys such as Gaia (ESA). In this work we present a tool to generate realistic Gaia mock catalogues, which consists of test particle simulations integrated using a realistic 3D Galactic potential and where we have assigned to each particle the characteristics of disc Red Clump K giants stars (hereafter, RC stars). Using an extinction model and the Gaia selection function and error model, we can define a mock catalogue for each particular problem.

In our case, we are interested in gauging the capabilities of Gaia to characterize the Galactic bar, in particular, in determining its angular orientation.

2 The generation of the mock catalogue

In order to generate Gaia mock catalogues we need the following ingredients:

First, a set of initial conditions. In our case, we use the Hernquist method [10] to generate a set of particles that follow the Miyamoto-Nagai disc density profile [11] and they are given velocity dispersions similar to that of the RC stars. The dispersions are obtained from the first order moments of the collisionless Boltzmann equation, simplified by the epicyclic approximation. The values at the solar position are $\sigma_U = 30.3\mathrm{km\,s^{-1}}$, $\sigma_V = 23.6\mathrm{km\,s^{-1}}$and $\sigma_W = 16.6\mathrm{km\,s^{-1}}$[4, and references therein]. We also assume a constant scale-height of 300pc [12]. The number of particles is normalized to the solar surface density according to the New BGM [5], in the case of the RC stars 57M particles.

Second, a realistic 3D Galactic potential. It consists of an axisymmetric component, the well-known Allen& Santillan potential [1] with a spherical bulge, a Miyamoto-Nagai disc (with the same parameters as in the initial conditions) and a spherical halo, with a total mass of $9 \times 10^{11}\,M_\odot$. We use the superposition of two Ferrers ellipsoids [8] so that the Galactic bar looks like a boxy/bulge, i.e. the COBE/DIRBE triaxial bulge, plus the long ends. For the COBE/DIRBE bulge we set the semi-major axis to $a = 3.13$kpc and the axes ratios to $b/a = 0.4$ and $c/a = 0.29$. The mass is $M_{CB} = 4.5 \times 10^9\mathrm{M}_\odot$. The length of the Long ellipsoid is set to $a = 4.5$kpc and the axes ratios to $b/a = 0.15$ and $c/a = 0.026$. Its mass is fixed to $M_{LB} = 2.5 \times 10^9\ \mathrm{M}_\odot$. So finally we obtain a boxy/bulge type of bar with total mass equal to $M_b = 7. \times 10^9\mathrm{M}_\odot$. Both major axes are aligned on the x-axis of the rotating reference system but they are oriented at 20° from the Sun-Galactic Centre line. It rotates at a constant angular speed of $50\mathrm{km\,s^{-1}\,kpc^{-1}}$around the short z-axis. This value is within the range accepted for the COBE/DIRBE bar of the Milky Way [9]. In order to keep the total mass of the system constant, we introduce the Galactic bar adiabatically in four bar rotations, while we remove mass to the bulge. We use the same time function as in [6].

Third, a tracer population. As mentioned above, each test particle is treated as a disc RC star. Therefore, we assume they have an absolute magnitude of $M_K = -1.61$ [2] without intrinsic dispersion in brightness and intrinsic colors of $(V - I)_o = 1.0$ and $(V - K)_o = 2.34$ [2].

Fourth, an extinction model. In this work we use the Drimmel extinction model [7] with scaling factors to derive the visual absorption. We then use Cardelli's law ($A_K = 0.114A_V$ and $A_I = 0.479A_V$) to compute the apparent magnitude in V and the observed (V-I) colour index, necessary to obtain the Gaia, G, magnitude.

And fifth, an error model. We use the pre-commissioning error model as described in the Gaia Science Performace webpage to compute the astrometric, photometric and spectroscopic uncertainties, which will be convolved to the modelled data to finally obtain the observed

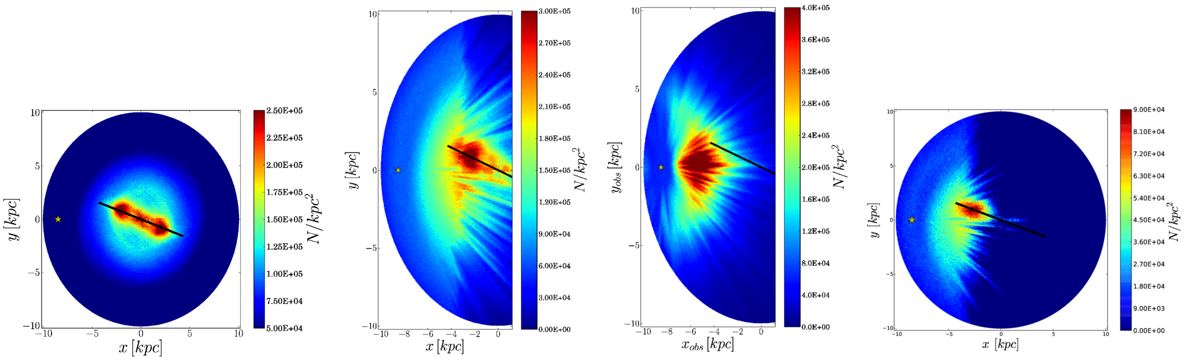

Figure 1: Surface densities. First: The RC-all catalogue. Second: The RC-G20 mock catalogue. Third: The RC-G20-O catalogue. Fourth: The RC-G20-IR catalogue. The black solid line outlines the position of the Galactic bar, while the yellow star shows the Solar position.

astrometric and radial velocity values. As a second example, we will consider that we can derive photometric distances from IR surveys, such as APOGEE or UKIDSS, and we can assume a fixed relative error in distance of 10%.

Using these ingredients, the output is a catalogue with 6D components (positions and velocities) real and observed, to which we will refer as RC-all sample. From this catalogue, we can generate the mock catalogues that best suits the particular problem. As a first scientific application, we consider all stars that Gaia we detect, that is, all stars with Gaia G magnitude $G \leq 20$. We will refer to this mock catalogue as RC-G20. When we convolve this catalogue with Gaia errors, we refer to it as RC-G20-O, while when we convolve it with IR distances, we refer to it as RC-G20-IR. In Fig. 1, we show the surface density of all four catalogues.

In Fig. 2 we show the mean relative error in parallax in the RC-G20 catalogue at two cuts in height. In the left panel, we consider all the stars within $|z| < 300\,\mathrm{pc}$ in galactocentric cylindrical bins (R, θ) of size 100pc $\times 0.72°$, where $R \in [0, 10]$kpc and $\theta \in [0, 360°]$. Thus, these stars are highly affected by extinction. In the right panel, we consider all the stars in the same galactocentric cylindrical bins but above $|z| > 300\,\mathrm{pc}$, so above the Galactic plane and less affected by extinction. As expected, the errors in parallax are also smaller in the regions above the Galactic plane allowing to reach farther from the Solar position.

3 The angular orientation of the Galactic bar

As seen in the previous section the errors in parallax close to the Galactic plane are very high near the Galactic bar region, making the observed sample to delete the signature of the Galactic bar (see right panel of Fig. 1). Therefore, it is a very complex task to determine the angular orientation of the Galactic bar with only Gaia data. However, the combination of Gaia data with photometric distances (RC-G20-IR mock catalogue) results a suitable sample to try to determine the angular orientation of the bar.

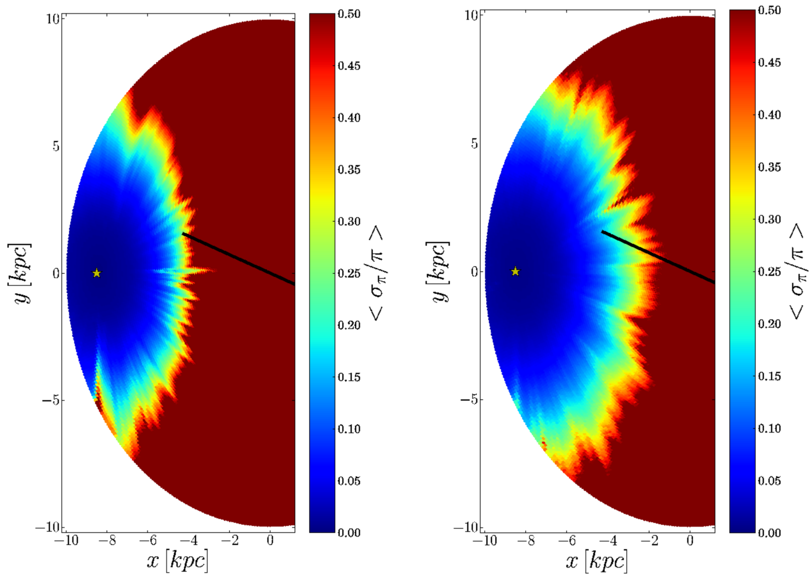

Figure 2: Relative error in parallax in the RC-G20 sample. Left: For stars within $|z| <$ 300 pc. Right: For stars above $|z| > 300$ pc. The black solid line outlines the position of the Galactic bar, while the yellow star shows the Solar position.

We develop a method to determine the azimuthal angle of the bar overdensity in our Gaia samples following two steps. First, we subtract the axisymmetric component to enhance the bar structure, and, second, we perform a Gaussian fit to the subtracted stellar overdensity to locate the angular position of the maximum stellar density. The procedure is as follows:

1. Subtraction of the axisymmetric component. We make galactocentric radial bins of 100pc and we compute the mean surface density inside each ring. We then subtract the mean from the initial surface density map. From that we obtain an image with the non-axisymmetric components clearly enhanced.

2. Gaussian fit to the surface stellar overdenity. We make galactocentric polar bins of 400pc in radius and 0.72° of azimuthal width. For each radial ring, we fit a Gaussian function to the data using least squares. This allows us to derive the galactocentric azimuth at which the function has an absolute maximum (the mean of the fitted Gaussian). The error bar assigned to the azimuth of the maximum density is the 1σ error derived from the least square of the Gaussian fit.

This procedure has been applied to the RC-all and RC-G20-IR samples (Fig. 3). The RC-all sample allows us to check the performance of the method. We perform the Gaussian fit to the stars in the first heliocentric quadrant ($0 \leq l \leq 90°$), which is where the near side of the Galactic bar is located. In Fig. 3 we show in polar coordinates the azimuth obtained at each radial bin (green curve). The azimuthal angle is defined positively in the counter-clockwise direction from the x-positive axis. Thus, the points line up along the 160° constant azimuthal angle. Note that we recover the bar semi-major axis up to $R \sim 4$kpc, which corresponds to a radius intermediate between the one of the boxy/bulge bar and the one of the Long bar. The discrepancy at the end of the bar is clearly observed after $R > 3.5$kpc associated to the overdensity of the inner ring and the spiral arms. This discrepancy would indicate approximately the length of the bar.

We then apply the same procedure to the RC-G20-IR sample. First, note that again, the extinction blurs the contribution of the non-axisymmetric components to the surface density (see right panel of Fig. 1). However, we still can observe the near side of the Galactic bar. In Fig. 3, we show the azimuthal angle obtained for this sample (red curve). Although the good recovery, we observe a small bias of $\sim 3-5°$, deviated with respect to the nominal value in about $2-3\sigma$. Several factors account for this bias. First, the RC-G20-IR sample has the effects of the extinction model. Given a certain line-of-sight, the number of stars observed will decrease with the heliocentric distance. This fact can translate into a change of the bar maximum observed density towards higher values of θ. Second, the fact that the RC-G20-IR sample is magnitude-limited makes that intrinsically brighter stars are over-represented, this is the Malmquist bias. This can also lead to biased values of the azimuthal angle, which are not trivial to correct [3]. Third, there is also a geometric bias due to the fact that even having a symmetric error in photometric distance along the line of sight, it translates into a non-symmetric $\Delta\theta$ from the Galactic Centre. Only stars in a line-of-sight perpendicular to the semi-major axis of the bar will not suffer from this bias. In any case, even taking into account the possible biases, the Gaussian fit method recovers well the azimuthal angle of the Galactic bar.

Acknowledgments

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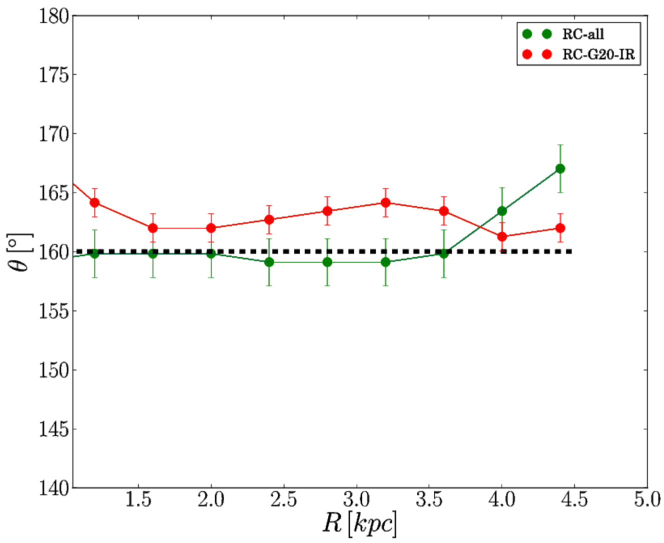

Figure 3: Determination of the bar azimuthal angle. We show in polar coordinates the result of the Gaussian fit to the RC-all sample (green curve) and RC-G20-IR sample (red curve). The horizontal thick black line corresponds to the imposed azimuthal angle in the model. The azimuth is defined positive counter-clockwise and from the x-positive axis. The bar, therefore, is located at 160°.

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