FROM DETAILED GALAXY SIMULATIONS TO A REALISTIC END-OF-MISSION GAIA CATALOGUE

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ABSTRACT

We address the problem of identifying remnants of satellite galaxies in the halo of our galaxy with Gaia data. We make use of N-body simulations of dwarf galaxies being disrupted in the halo of our Galaxy combined with a Monte Carlo model of the Milky Way galaxy. The models are converted to a simulated Gaia catalogue containing a realistic number ($\sim 10^8$–10^9) of stars. The simulated catalogue can be used to study how to handle the large data set that Gaia will provide and to study issues such as how to best retrieve information on substructure in the Galactic halo. The techniques described are applicable to any set of N-body simulations of (parts of) the Galaxy.

Key words: Gaia; Galaxy: formation, halo, structure.

1. INTRODUCTION

Cosmological models predict that halos of luminous galaxies are assembled through merging of smaller structures. Remnants of past mergers will survive for a long time in the halo as debris streams because of the very long dynamical time scale. The Gaia mission offers a unique opportunity to search for and study these remnants with full phase space information in our Galaxy's halo. However disentangling the possibly many remnants from each other and from the background of Galactic stars will be very challenging. The Gaia catalogue will contain about one billion objects of which the stars in the individual debris streams may form only a very small fraction. In addition, the streams are spread out all over the sky. Identifying them will require a combination of search methods that make use both of conserved dynamical quantities of the debris stream (such as energy and angular momentum, see e.g., Helmi et al., 1999; Helmi & de Zeeuw, 2000) and astrophysical properties of the constituent stars (from photometric data).

The goals of this work are: **1.** study the retrieval from Gaia data of remnants of satellite galaxies that have been disrupted in the potential of our Galaxy; **2.** include a realistic model of the Galactic background population against which the remnants have to be detected; **3.** gain practical experience with analysing and visualising the enormous volume of information that will be present in the Gaia data base.

To achieve this we built a Monte Carlo model of the smooth components of the Galaxy containing a realistic number of stars and performed tree-code N-body simulations of satellites that are disrupted while orbiting the Galaxy. The Galaxy and satellite models were subsequently combined and Gaia observations were simulated. In the following we summarise how the simulated Gaia survey was generated, with emphasis on the proper combination of the satellite and Milky Way models, and we present some examples of the simulated Gaia data. For details we refer to Brown et al. (2004).

2. MONTE CARLO MODEL OF OUR GALAXY

The Milky Way model consists of three spatial components: a bulge with a Plummer density law, a double exponential disc, and a flattened halo ($c/a = 0.8$) for which the density drops as $r^{-3.5}$. The kinematics are modelled in a very simple manner: each component rotates with constant velocity dispersion, for the bulge an isotropic dispersion is assumed, for the disc a different velocity ellipsoid is used for each spectral type (OBAFGKM), while for the halo the dispersions are the same for each spectral type. The individual stars are assigned an absolute magnitude M_V and a colour $(V-I)$ from a Hess-diagram which is considered fixed for all Galactic components and all positions throughout the Galaxy. The Hess-diagram is taken from Table 4–7 of Mihalas & Binney (1981) and provides the relative numbers of stars in bins of absolute magnitude (M_V) and spectral type. These numbers integrated over spectral type provide the luminosity function. Although this is a highly simplified and certainly not self-consistent model of the Galaxy it is good enough for providing the 'background' distribution in phase space against which the debris streams have to be found.

For a magnitude limited survey, as is the case for Gaia, a straightforward Monte Carlo realisation of the Galactic model is potentially a very wasteful procedure. Most simulated stars will be too faint to be included in the survey. Hence we used a strategy that minimizes wasted effort by generating stars only within the magnitude limited

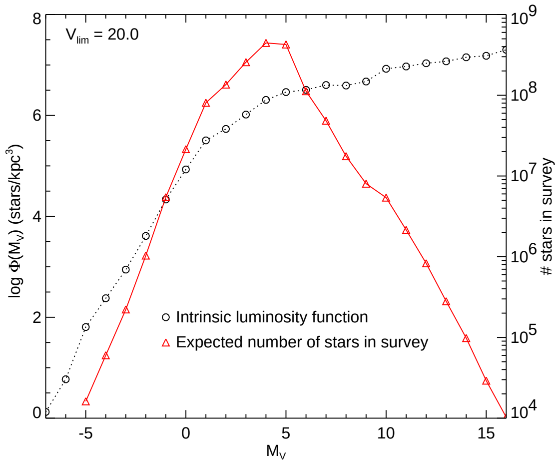

Figure 1. Intrinsic (circles, left vertical scale) and weighted (triangles, right vertical scale) luminosity functions for our Milky Way model plotted vs. M_V. The weighted luminosity function is plotted in terms of the number of stars expected in the simulated Gaia survey.

sphere centred on the observer. This results in a Galaxy model with a luminosity function that is weighted by the space density integrated over the volume limited sphere for each spectral type. This luminosity function is shown in Figure 1. Nevertheless the generation of the Monte Carlo model is still a large computational task and in order to save time we decided not to simulate the part of the sky within Galactic coordinates: $-90° \leq \ell \leq +90°$ and $-5° \leq b \leq +5°$. Tracing the debris streams in this part of the sky will be difficult in practice due to the large extinction in those directions. In our Galactic model ~80% of the stars lie in this region of the sky as seen from the Sun for a survey limited at $V = 20$. The resulting simulated survey of the Galaxy is fully sampled and contains 3.2×10^8 stars. For each of these we generated the 6 phase space coordinates (positions and velocities), an absolute magnitude, a population type (bulge, disc or halo) and a spectral type.

3. N-BODY MODELS OF DWARF GALAXIES

The models of the debris streams were generated by simulating the disruption of dwarf galaxies orbiting our Galaxy. The Milky Way is represented by a rigid potential which is derived from a mass-model consisting of: a double exponential disc, a spherical bulge with Hernquist profile, and a logarithmic Halo potential with flattening $c/a = 0.8$. The dwarf galaxies are represented by King models (King, 1966) with a mass of 5.6×10^6 $M_\odot$ or 2.8×10^6 $M_\odot$ and 10^6 particles. The tidal radius and concentration parameter $c = \log(r_t/r_c)$ are 3150 pc and 0.9, respectively. The satellites are placed on five different orbits which vary in apocentre, pericentre and the initial inclination with respect to the Milky Way's disc. The simulations were evolved with a tree-code for ~10 Gyr. Multiple debris streams can be simulated by combining different N-body snapshots (different orbits and/or ages), and each snapshot can be rotated around the Z-axis or

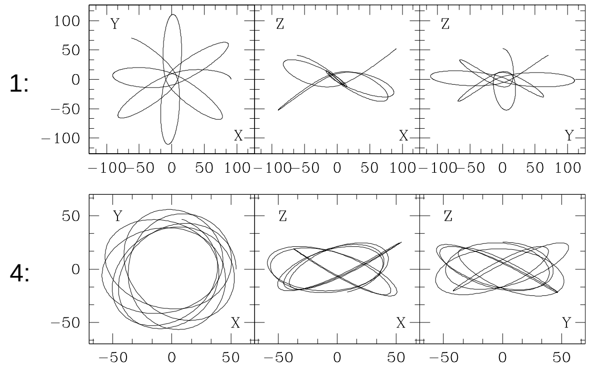

Figure 2. Satellite orbits for models no. 1 and 4 projected onto the principal axes of our Milky Way galaxy model. The Galactic plane corresponds to the XY projection. Distances are in kpc.

flipped with respect to the disc plane. Two of the orbits for the N-body satellites are shown in Figure 2. All stars of a given dwarf galaxy are assumed to be of the same age. Masses are drawn from a mass-function and M_V and $(V-I)$ are derived from a low-metallicity isochrone (from Girardi et al., 2000) of the appropriate age.

4. MODELLING THE GAIA SURVEY

The 6 phase space coordinates $(\mathbf{r}, \mathbf{v})$ for each star in the Galaxy and satellite model are referred to the Solar position and velocity and converted to the 5 astrometric parameters; position (ℓ, b), parallax ϖ, proper motions $\mu_{\ell *} = \mu_\ell \cos b$ and μ_b, and the radial velocity $v_{\rm rad}$. The conversion is done using the standard prescriptions for transforming Cartesian position and velocity coordinates into astrometric parameters and radial velocities, such as described in Volume 1, Section 1.5.6, of the Hipparcos Catalogue (ESA, 1997). The astrometric errors are added as a function of G (Gaia broad band magnitude) and $(V-I)$:

$$\sigma_\varpi \simeq (7 + 105z + 1.3z^2 + 6 \times 10^{-10} z^6)^{1/2} \times [0.96 + 0.04(V-I)] \, , \quad (1)$$

where $z = 10^{0.4(G-15)}$ and

$$G = V + 0.51 - 0.50 \times \sqrt{0.6 + (V-I-0.6)^2} - 0.065 \times (V-I-0.6)^2 \, . \quad (2)$$

The parallax errors for the simulated Gaia data of the Milky Way model are shown in Figure 3. The mean position and proper motion errors are $\sigma_0 = 0.87\sigma_\varpi$ and $\sigma_\mu = 0.75\sigma_\varpi$, respectively, and the variation of the astrometric errors with ecliptic latitude β is included. The radial velocity errors for OBA-type stars are 0.25, 4, 10, 50 km s^{-1} at $V = 10, 15, 16, 17$, respectively. For FGKM-type stars the errors are 0.1, 1, 2, 6 km s^{-1} at $V = 10, 16, 17, 18$. For stars fainter than $V = 17$ (OBA) or $V = 18$ (FGKM) radial velocities are not available. These error prescriptions are according to the Gaia Concept and Technology Study Report (ESA, 2000).

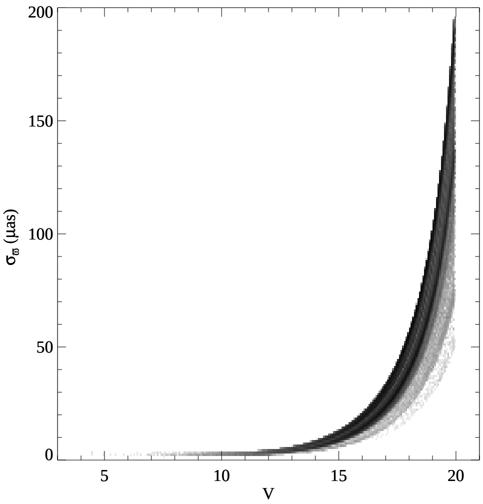

Figure 3. Parallax errors vs. V-magnitude in the simulated Gaia catalogue for 1 million stars from the model Milky Way. The grey scale indicates the number of stars. The spread in the values at each V is caused by the colour dependence of the errors (see Equation 1).

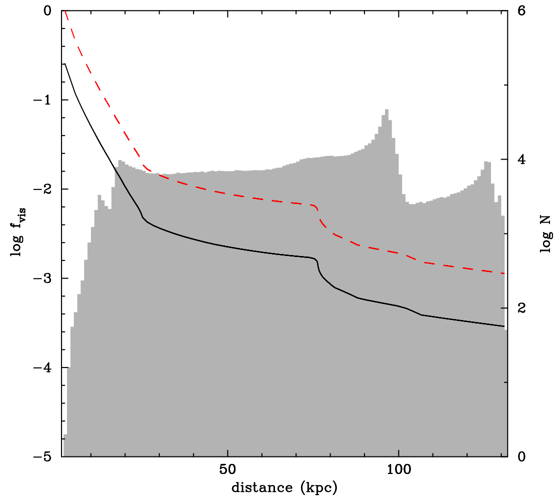

Figure 4. f_i vs s_i for satellite model 1. The shaded histogram (right vertical scale) shows the distribution of s_i. The solid line (left vertical scale) shows $f_i(s_i)$. Features in this line reflect features in the luminosity function. The dashed line shows the $f_i(s_i)$ when assuming all N-body stars to be brighter than the faintest satellite star that enters the Gaia survey. We calculated f_i using a 10 Gyr isochrone with $Z = 0.004$ and $\xi(m) \propto m^{-1.5}$. The overall fraction of visible N-body particles is only 2.5×10^{-3} (!) and 10^{-2} for the two cases considered.

4.1. Combining the Simulated Milky Way and Satellite Data

Having made a considerable effort to realistically simulate the number of Galaxy stars that is expected to be seen by Gaia, we want to ensure that the satellite simulations are properly added to the Galaxy data. This means that the number of satellite particles in our simulated Gaia catalogue should be a realistic fraction of the number of Galactic particles. Getting this right is not trivial and we explain our solution to this problem here.

Given a certain distribution of stars along the orbit of a particular dwarf galaxy (corresponding to an N-body 'snap-shot'), the number of stars from this satellite that will end up in the Gaia catalogue depends on three factors: **1.** The overall number stars (i.e., luminous particles) in the dwarf galaxy. This number is determined by its overall luminosity and the stellar mass function. **2.** The Gaia survey limit leads to an upper limit $M_{V,\max}$ on the absolute magnitude of visible satellite stars. **3.** The variation of $M_{V,\max}$ along the satellite orbit, caused by a variation in distance from the Sun.

At each distance s_i where an N-body particle is located the fraction of visible satellite stars f_i can be calculated:

$$f_i(s_i) = \frac{\int_{m(M_{V,\max})}^{m_{\mathrm{up}}} \xi(m)dm}{\int \xi(m)dm} \qquad (3)$$

where $M_{V,\max}(s_i) = V_{\mathrm{lim}} - 5\log s_i + 5$, while $\xi(m)$ is the mass function and m_{up} its upper limit. The overall fraction f of visible N-body stars is $f = \sum_i f_i(s_i)/N_{\mathrm{sim}}$. As Figure 4 illustrates the overall fraction of visible stars for a fully populated mass function can be very small depending on the distribution of satellite stars along the orbit. In addition we are faced with the problem that real dwarf galaxies contain up to 10^9 stars but our N-body models contain 1 million particles only. Of these 'expensive' N-body particles we want to waste as little as possible. An obvious step is to assume that all N-body particles represent stars that are brighter than the faintest star that can enter the Gaia survey given the distance distribution of the N-body particles. This will raise the overall visible fraction N-body particles as illustrated by the dashed line in Figure 4.

This hints at the following solution: assume that all N-body particles represent a bright tracer population, such as AGB stars. That is, $M_V \leq M_{V,\mathrm{tracer}}$ for all particles. This will further raise the overall visible fraction f. The details of this procedure are discussed in Brown et al. (2004) where it is shown that depending on the total luminosity (mass) of the simulated satellite one can then easily retain the majority of the N-body particles while still preserving the variation of the visible fraction of tracer stars along the debris stream.

5. TRACING DEBRIS STREAMS IN THE GAIA CATALOGUE

Various methods have been proposed and used to recover satellite remnants from surveys of Galactic phase space. Figure 5 shows an example of energy vs angular momentum (E–L_z) diagrams. For this figure we combined 18 million stars from the Monte Carlo model of the Galaxy with the satellite models 1 (at 10 Gyr) and 4 (at 5 Gyr). The value of $M_{V,\mathrm{tracer}}$ is 0.4 and 1.0 respectively. Keep in mind that the figures under-represent the real contrast between Galaxy and satellite.

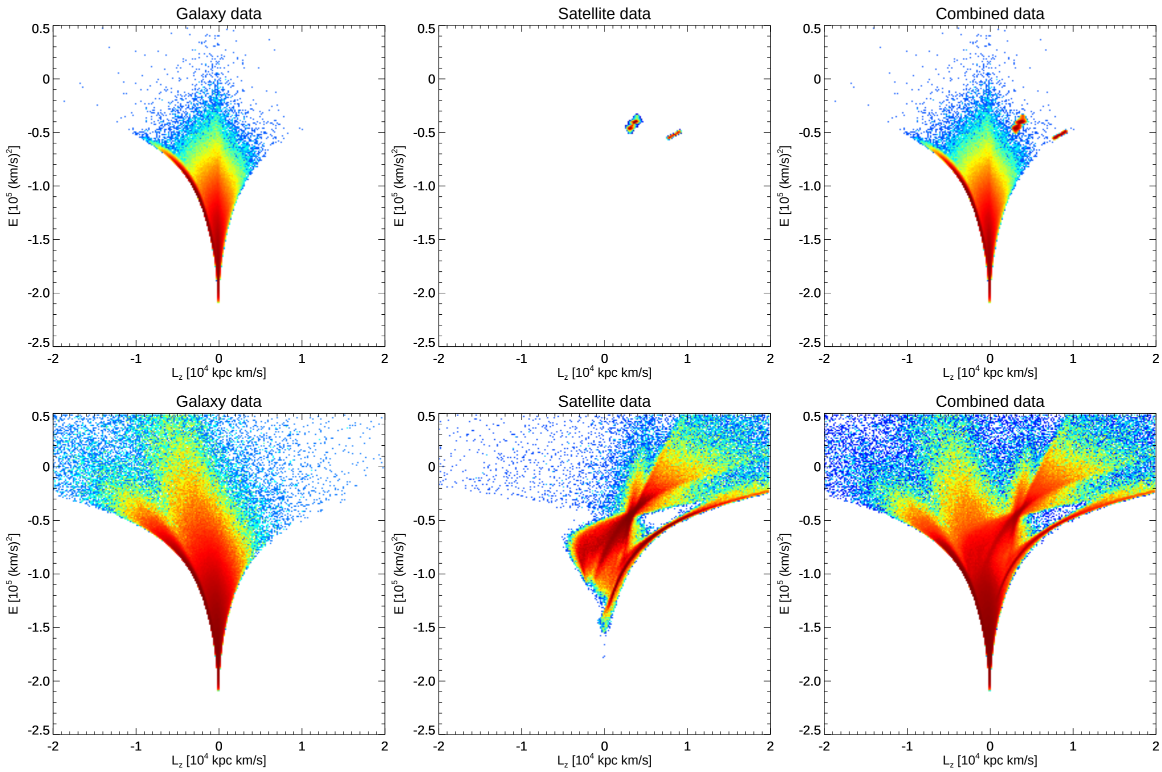

Figure 5. Energy vs angular momentum diagrams. The top row shows the true (simulated) E–L_z distribution and the bottom row the energy and angular momentum as they would appear when derived from the Gaia catalogue. From left to right the panels show the data for the Monte Carlo model of the Milky Way, for the two satellites (models 1 and 4 at 10 and 5 Gyr, respectively), and the combined data. Only stars with positive parallaxes and available radial velocities are shown. Note how the compact E–L_z distribution of the debris streams turns into a more complex structure in the lower diagrams due to the way the astrometric and radial velocity errors propagate. The parallax errors (see Figure 3) are by far the dominant contribution to these structures.

6. FUTURE WORK

We intend to use this work to study in detail the retrieval of debris streams from the Gaia catalogue by making use of the accurate phase space data that Gaia will provide throughout the Galaxy. However, as can be appreciated from the E–L_z diagrams shown in Figure 5 it will not be possible to trace complete debris streams based on phase space data alone. Fortunately, using the photometric information from Gaia will provide astrophysical parameters for the different stellar populations. This will enable a drastic narrowing down of the parts of the Gaia catalogue that need to be searched. Investigating this will require improvements to the simulations.

The simulation of actual Gaia photometry from the broad and medium band photometers is possible using the tools developed at the University of Barcelona (see the contributions by Jordi et al. and Carrasco et al. in this volume). An extinction model can be included in an approximate way using currently available 3D extinction models such as the one presented by Drimmel et al. (this volume). Finally, if in reality the Galactic halo has not had time to relax and wipe out the clumpy remnants of past merger events, it will be necessary to replace the smooth halo component in our Milky Way model with a clumpy one.

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