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# SEARCHING FOR GHOSTS IN THE GALACTIC HALO: WHAT CAN WE LEARN ABOUT THE FORMATION OF THE GALAXY FROM THE STELLAR HALO?

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RESUMEN

Presentamos un estudio de la factibilidad de recuperar información de remanentes de galaxias satélite, que han sido destruidas en el halo Galáctico, usando astrometría espacial de *Gaia*. Esta misión proveerá una base de datos para un gran número de estrellas ($\sim 10^9$), con un nivel de precisión extraordinario (decenas de $\mu$s). Sin embargo, antes de intentar recobrar información útil, se debe estudiar el efecto de sesgos de muestreo, errores observacionales y la contaminación por el fondo galáctico estelar.

Presentamos una simulación de Monte Carlo del catálogo de *Gaia* que excluye el disco galáctico ($|b| < 5°$) en el primer y cuarto cuadrantes de la Galaxia. El catálogo simulado contiene un número realista de estrellas ($3 \times 10^8$), para cada una de las cuales se ha simulado información cinemática y fotométrica. No incluimos los efectos de absorción interestelar. Simulamos la destrucción de galaxias satélite en el halo Galáctico usando satélites de $10^6$ partículas que se mueven dentro de un potencial rígido que representa a la Galaxia. Información fotométrica es añadida suponiendo isócronas particulares para cada satélite, e incorporando cuadros de la simulación de $N$–cuerpos al catálogo simulado. Toda la información de espacio fase es convertida a observables astrométricas y se añaden errores observacionales a partir de un modelo realista que incluye dependencia en la magnitud aparente, color y latitud eclíptica de las estrellas.

Probamos la factibilidad de identificar fusiones pasadas de satélites en diagramas de energía contra momento angular. Concluimos que la identificación es posible, pero debe hacerse una pre-selección de estrellas con información de alta señal a ruido, asi como usar criterios fotométricos. La herramienta numérica que hemos desarrollado puede ser usada para probar la efectividad de otras estrategias de búsqueda.

ABSTRACT

We study the feasibility of recovering information of remnants of tidally disrupted satellite galaxies in the halo of our Galaxy, using space astrometry from *Gaia*. This mission will provide a very large data set ($\sim 10^9$ stars) with an unprecedent level of detail in phase space (tens of $\mu$s). However, before recovering useful information, sampling biases, observational errors and the stellar galactic background must be taken into account.

We present a Monte Carlo simulation of the *Gaia* catalogue that excludes the galactic disk ($|b| < 5°$) within the first and fourth galactic quadrants. The simulated catalogue contains a realistic number of stars ($3 \times 10^8$), and for each we have simulated kinematic and photometric information. No interstellar extinction is included. We simulate the destruction of satellite galaxies in the Galactic halo, using $10^6$–particle satellites moving within a fixed potential that represents the Galaxy. Photometric information is added assuming particular isochrones and simulation snapshots are added to the simulated catalogue. All phase-space data is converted to astrometric observables. We then add observational errors to all simulated *Gaia* observables according to a realistic model that includes dependence on apparent magnitude, color and ecliptic latitude.

We test the feasibility of recovering past merger signatures in the energy *vs.* angular momentum plane. We conclude that recovery is possible, but a pre-selection of high signal-to-noise data as well as complementary photometric criteria must be used. The numerical tool here developed can be employed to test the feasibility of other search criteria.

*Key Words:* **METHODS: NUMERICAL — GALAXY: FORMATION — GALAXY: STRUCTURE — GALAXIES: INTERACTIONS**

## 1. INTRODUCTION

The existence of substructure in galactic halos is a natural consequence of current cosmological mod-

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els that envisage the hierarchical assemblage of large structures from the merger of smaller ones (Kauffmann and White 1993). Such scenario must have left an imprint in the halo of large galaxies like ours, where the long dynamical timescales help preserve this fossil evidence (Lynden–Bell 1976). Furthermore, substructure is detected in the Galactic halo (e.g., Ibata, Gilmore & Irwin 1994). This converts the halo of our Galaxy in a convenient nearby cosmological laboratory to test the current cosmological paradigm (Freeman & Bland–Hawthorn 2002).

The *Gaia* astrometric mission has been selected by *ESA* as a cornerstone mission to be launched around 2012. Its objective includes the census of all stars brighter than magnitude $V = 20$ and determination of their astrometry, photometry and, in the case of stars brighter than $V \sim 17$–18, measurement of their radial velocity (ESA 2000). This database will provide us with a global view of the galactic halo at an unprecedent level of detail.

In order to use the *Gaia* database to make a survey of substructure in the Galactic halo, from which we could learn about the process that lead to its formation, it is necessary to study beforehand the subtle effects that arise from the sampling process, the blurring of information due to observational errors and the difficulties of extracting the relevant information against a stellar halo background.

In this contribution we present a Monte Carlo simulation of the *Gaia* database and use it, together with $N$–body simulations of the destruction of galaxy satellites within the Galactic halo, to test the feasibility of identifying substructure in the integrals of motion space (Helmi & de Zeeuw 2000). In § 2 we describe the Monte Carlo model of the Galaxy and in § 3 the $N$–body simulations of the satellites and their incorporation into the Galaxy catalogue. In § 4 we show the results in integral of motion space and § 5 is a summary of our main results. All of this is presented very briefly. Interested readers should consult Brown, Velázquez & Aguilar (2005).

## 2. THE MONTE CARLO MODEL OF THE GALAXY

To generate a mock catalogue of the *Gaia* database we need a luminosity and kinematical model for the Galaxy. For the luminosity distribution of the Bulge we assume a Plummer model with a core radius of 0.38 kpc; for the disk we assume a double exponential with scale lenght 8.5 kpc, and scale height 0.2 kpc; the stellar halo is a flattened model (axes ratio 0.8), with a core radius of 1 kpc, that goes as $r^{-3.5}$ at large distances. This model is normalized to a luminosity density of $6.7 \times 10^{-2}$ $L_\odot/pc^3$, and bulge to disk and halo to disk ratios of $5.5 \times 10^{-5}$ and $1.25 \times 10^{-3}$, respectively; all at the solar neighborhood. This results in a total luminosity of $3.2 \times 10^{12}$ $L_\odot$, with global bulge to disk, and halo to disk ratios, of 0.20 and 0.17, respectively.

For the kinematics, we assume that the bulge does not rotate and has a velocity dispersion of 110 km/s. For the disk we assume a rotation of 220 km/s with a spectral–type dependent velocity ellipsoid. The halo is assumed to rotate at 35 km/s with a triaxial velocity ellipsoid ($\sigma_R = 135$, $\sigma_\theta = 105$, $\sigma_z = 90$ km/s). In all cases, the velocity ellipsoids are fixed in cylindrical coordinates. Although this is a very simple model, it is good enough to provide the "background" in our study.

The final ingredients are a stellar luminosity function and spectral type distribution. For this we have used table 4-7 of Mihalas & Binney (1981). We assume that these distributions are the same all across the Galaxy.

The mock catalogue contains position, velocity, absolute magnitude and population type for each star. We have not included the effects of interstellar extinction, as we are interested in the halo, only. Additionally, to speed up the mock catalogue generation, which is the most time consuming part of this work, we have left out the galactic disk in the first and fourth quadrants ($-90° < l < 90°$, $|b| < 5°$). Our final catalogue contains $3.5 \times 10^8$ stars.

All these quantities are then converted to position in the sky, parallax, proper motion, radial velocity and photometric information for each star. Simulated observational errors are then added. The errors in the astrometry vary with the apparent magnitude, color and, because of the way *Gaia* will scan the sky, on ecliptic latitude. Errors in the radial velocity depend on apparent magnitude and spectral type. We have followed Perryman (2002) and ESA (2000).

## 3. THE $N$–BODY SIMULATIONS OF THE SATELLITES

We have performed $N$–body simulations of the destruction of satellite galaxies orbiting around the Galaxy. The satellites are self–consistent $10^6$–particle King models with a concentration of 0.9 and a tidal radius of 3.15 kpc. We have used two masses: $2.8 \times 10^7$ and $5.6 \times 10^7$ $M_\odot$.

The Galaxy is represented by a rigid mass model. The bulge is a Hernquist model (Hernquist 1990) with a mass of $1.4 \times 10^{10}$ $M_\odot$ and a characteristic

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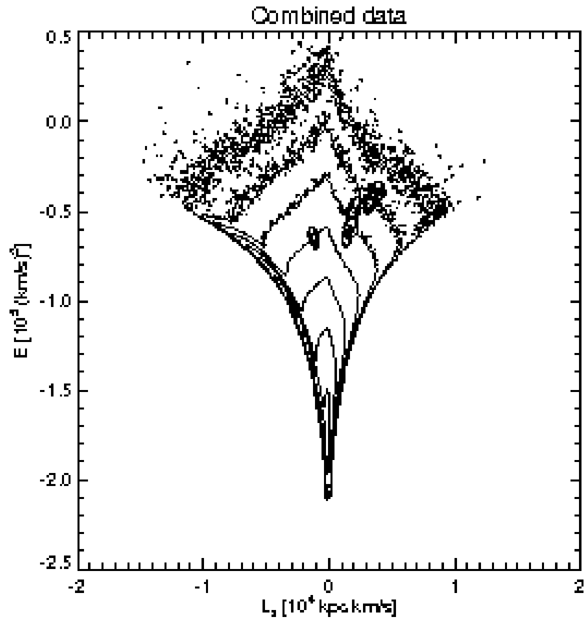


Fig. 1. Projection in $E$–$L_z$ of our mock catalogue together with three simulated satellites. The curves are iso–density contours in this projection, equally spaced in a logarithmic scale. This figure shows error–free data.

radius of 0.63 kpc. The disk is a double exponential (Quinn & Goodman 1986) of mass $5.6 \times 10^{10}$ $M_\odot$ with a scale length of 3.5 kpc and scale height of 0.7 kpc. The halo is an oblate, truncated isothermal model with core (Binney & Tremaine 1987) of axis ratio 0.8, core radius 12 kpc, and circular velocity of 186 km/s. The truncation radius is 200 kpc and the overall mass of the mass model is $1.7 \times 10^{12}$ $M_\odot$.

We have used a parallel tree code (Dubinski 1996) running in a 32-processor beowulf cluster (Velázquez & Aguilar 2003). We ran 5 simulations with satellite orbital eccentricities that range from 0.20 to 0.88, inclinations with respect to the galactic disk from 25° to 60°. The simulated time was 10 Gyr. Energy conservation was 0.1% or better in all cases.

We selected various snapshots from our simulations and added them to the mock catalogue. For this we choose absolute magnitudes and colors from low-metallicity isochrones (Girardi et. al 2000) assigned at each snapshot according to the simulated time. We also need a mass function, for this we have used a power law ($\propto m^{-1.5}$). All this information was converted to *Gaia* observables according to the description in § 2.

There is, however, a sampling bias that must be addressed before adding the satellite data to the Galaxy data. Since satellite $N$-body particles are spread along a tidal streamer at a given snapshot, the distance to the observer can vary by a large factor. Since the *Gaia* survey is magnitude limited, this results in a varying probing depth of the satellite luminosity function as a function of position along the streamer. In order to properly account for this, we must discard $N$-body particles along the streamer according to the fraction of satellite stars that are visible at each position. This is a very wasteful procedure that may result in more than 99% of the simulation being thrown away! The proper thing to do is to simulate a bright tracer population of the satellite only. The luminosity cutoff for this population is obtained as a compromise between the opposing demands of keeping the largest number of $N$-body particles and properly simulating the varying probe depth along the streamer. This compromise depends, among other things, on the absolute magnitude of the satellite and its orbit. This is an important observational bias that must be taken into account, if one is to predict accurately the variation in star counts for tidal streamers on the celestial sphere.

## 4. RESULTS IN INTEGRAL OF MOTION SPACE

As a satellite is torn apart by the tidal force of the Galaxy, its remnant is spread along the original orbit of the satellite, this spreads the satellite stars over large regions of the sky and makes its identification a difficult job. However, except for the effect of dynamical friction, its energy (assuming a steady state galaxy) and angular momentum (assuming an axially symmetric galaxy) are conserved. Helmi and de Zeeuw (2000) have suggested searching for satellite remnants in a plot of these quantities.

Figure 1 shows our mock catalogue projected in energy versus angular momentum space. Despite the galactic background, the three satellites included in this figure are clearly visible around $E \sim -0.5$ and $0 < L_z < 0.5$; however, this is the error–free data.

Figure 2 shows what happens when we include observational errors. A very different picture arises. The satellite signatures have spread over large swaths and we would be hard pressed to find the number of satellites in it. Despite the high astrometric accuracy of *Gaia*, observational errors quickly increase toward the faint end of the survey. The parallax error, in particular, has a very large effect in the astrometry and produces the very extended smudges.

The previous discussion suggest a solution: avoid the faint end of the survey. Figure 3 shows the result

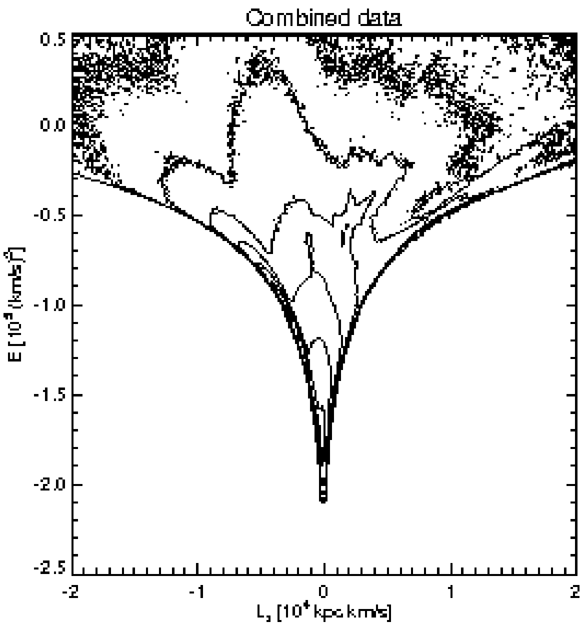


Fig. 2. Same as figure 1, but with observational errors included.

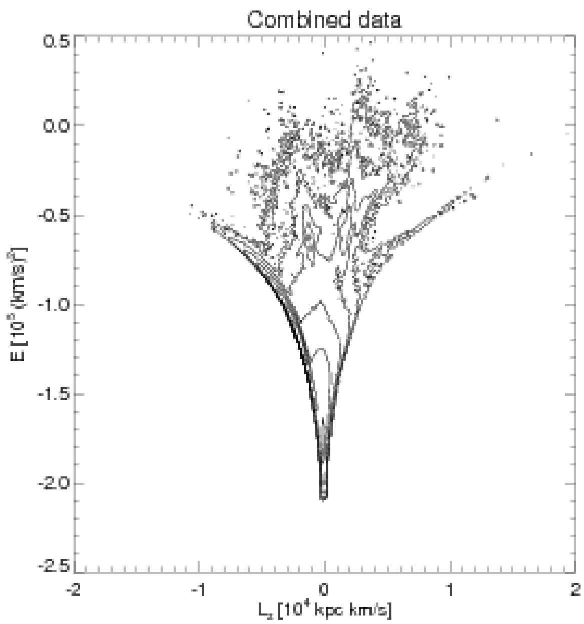


Fig. 3. Same as figure 2, but restricted to stars brighter than $V = 15$.

when we restrict the sample to stars brighter than $V$ =15. Although the situation is still messy, the nuclei of the satellites is recovered and can help us trace the rest of the remnant. It is obvious that a search in the $E$–$L_z$ plane must be restricted to high–quality signal. Since *Gaia* includes photometric information, a clever preselection in terms of this additional information will improve the search. We are currently exploring this.

## 5. SUMMARY

We have built a mock catalogue to asses the feasibility of searching for substructure in the Galactic halo with *Gaia*. We have included a realistic model for observational errors, the effect of non–uniform sampling along the tidal streamers and the presence of a galactic background. We have used this catalogue to test the feasibility of identifying past mergers using the $E$–$L_z$ diagram and found that this approach is possible, however, a preselection of high–quality data is necessary. This approach may be further enhanced by using photometric criteria to enhance the contrast of the satellite population against the galactic background. We are currently studying this approach. Full details on this study can be found in Brown, Velázquez & Aguilar (2005).

## REFERENCES

Binney, J. & Tremaine, S. 1987, Galactic Dynamics, Princeton University Press

Brown, A. G. A., Velázquez, H. M. & Aguilar, L. A. 2005, MNRAS, 359, 1287

Dubinski , J. 1996, New Astronomy, vol. 1, 133

ESA 2000, *Gaia* Concept and Technology Study Report, ESA–SCI(2000)4

Freeman, K. C. & Bland–Hawthorn, J. 2002, ARA&A, 40, 487

Girardi, L., Bressan, A., Bertelli, G. & Chiosi, C. 2000, A&AS, 141, 371

Helmi, A. & de Zeeuw, P. T. 2000, MNRAS, 319, 657

Hernquist, L. 1990, ApJ, 356, 359

Ibata, R., Gilmore, G., & Irwin, M. 1994, Nature, 370, 194

Kauffmann, G., & White, S. D. M. 1993, MNRAS, 261, 921

Lynden–Bell, D. 1976, MNRAS 174, 695

Mihalas, D. & Binney, J. 1981, Galactic Astronomy: Structure and Kinematics, 2nd. ed., New York NY, W. H. Freeman & Co.

Perryman, M. A. C. 2002, in Bienaymé O., Turon, C., eds, *Gaia*: A European Space Project, EAS Pub. Ser. Vol. 2, EDP Sciences, p. 3

Quinn, P.J. & Goodman, J. 1986, ApJ, 309, 472

Velázquez, H. & Aguilar, L.A. 2003, Rev. Mex. Astron. Astrof., 39, 197

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