

DETECTING HALO SUBSTRUCTURE IN THE GAIA ERA

C. Mateu,^{1,4} L. Aguilar,² G. Bruzual,¹ A. Brown,³ O. Valenzuela,² L. Carigi,²
H. Velázquez,² and F. Hernández^{1,4}

RESUMEN

Los datos observacionales que serán arrojados por la misión astrométrica Gaia, representan una oportunidad sin precedentes para la búsqueda de corrientes estelares utilizando información completa en espacio de fase y con una cobertura de todo el cielo, para un millardo de estrellas en nuestra Galaxia. En esta contribución describiremos el Método Modificado de Conteos en Círculos Máximos (mGC3), desarrollado para la detección de corrientes estelares de marea en el halo galáctico. Basado en el método GC3 originalmente propuesto por Johnston, Hernquist, & Bolte (1996), mGC3 incluye información de velocidad, con el fin de incrementar el contraste de las señales correspondientes a las corrientes estelares con respecto al fondo producido por el halo galáctico. Presentamos resultados de la eficiencia de mGC3, evaluada utilizando simulaciones de N cuerpos de corrientes estelares embebidas en un catálogo ficticio del fondo galáctico, incluyendo para éstos realizaciones realistas de sus propiedades fotométricas, cinemáticas, errores observacionales y límites de completitud. Caracterizamos la eficiencia de mGC3 como función de la luminosidad inicial, historia de formación estelar y parámetros orbitales de los satélites y encontramos que satélites con luminosidades en el intervalo $10^8 - 10^9 L_{\odot}$ pueden ser recuperados para edades dinámicas tan avanzadas como ~ 10 Gyr y hasta distancias galactocéntricas de ~ 40 kpc. Para algunas combinaciones de edades dinámicas y órbitas, es posible recuperar corrientes estelares con luminosidades hasta de $4 - 5 \times 10^7 L_{\odot}$.

ABSTRACT

The observational data expected to come from the Gaia astrometric mission represent an unrivaled opportunity to search for tidal streams using all-sky full phase-space information for nearly a billion stars in our Galaxy. In this contribution we will describe the Modified Great Circle Cell Count (mGC3) method devised for the detection of stellar streams in the galactic halo. This method is based on the GC3 method originally devised by Johnston, Hernquist, & Bolte (1996), modified to include velocity information in order to enhance the contrast of stream signatures with respect to the galactic halo background. We present our results on the efficiency of mGC3, tested by embedding tidal streams from N -body simulations in a mock Gaia catalogue of the galactic background, which includes a realistic realization of the photometric and kinematic properties, errors and completeness limits. We investigate mGC3's efficiency as a function of initial satellite luminosity, star formation history and orbital parameters and find that satellites in the range $10^8 - 10^9 L_{\odot}$ can be recovered for streams as dynamically old as ~ 10 Gyr and up to galactocentric distances of ~ 40 kpc. For some combinations of dynamical ages and orbits, tidal streams with luminosities down to $4 - 5 \times 10^7 L_{\odot}$ can be recovered.

Key Words: Galaxy: formation — Galaxy: structure — galaxies: interactions

1. INTRODUCTION

The Gaia astrometric mission will provide an outstanding catalogue of full phase-space information for a billion stars in the Galaxy, in an unbiased all-sky survey (de Bruijne 2012). This will provide an unprecedented opportunity for galactic archeology studies seeking to understand the processes that

were at play during the formation of the Milky Way (MW). In particular, the search for stellar streams in the galactic halo provides a key tool for disentangling some of the building blocks that have contributed to the formation of the MW, as well as for tracing the potential of the underlying dark matter halo (Freeman & Bland-Hawthorn 2002).

In the following contribution we will present the ‘modified Great Circle Cell Counts (GC3)’ method devised for the identification of tidal stellar streams in the galactic halo and present an analysis of the method’s efficiency, taking into account the appropriate observational errors and completeness limits expected for Gaia data.

¹Centro de Investigaciones de Astronomía, Av. Alberto Carnevalli, Sector La Hechicera, Apdo. Postal 264, Mérida 5101-A, Mérida, Venezuela (cmateu@cida.ve).

²Instituto de Astronomía, Universidad Nacional Autónoma de México, Mexico.

³Leiden Observatory, The Netherlands.

⁴Universidad de los Andes, Mérida, Venezuela.

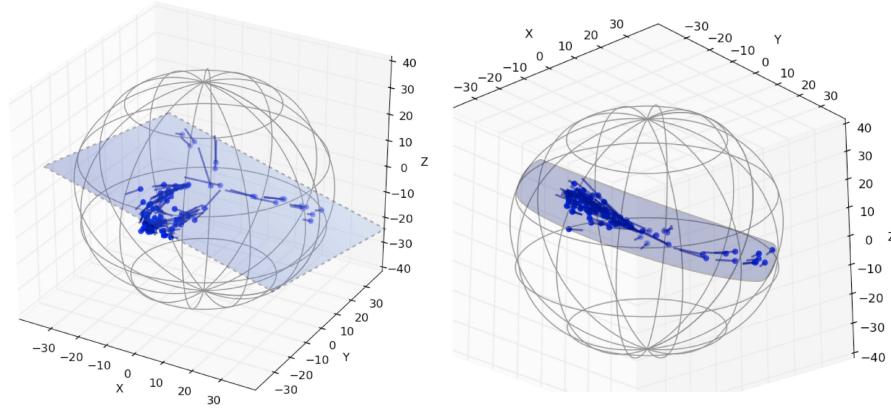


Fig. 1. 3D views of the spatial distribution and velocity field of a tidal stream simulation from Brown, Velázquez, & Aguilar (2005). The color figure can be viewed online.

2. THE MODIFIED GC3 METHOD

The modified Great Circle Cell Counts method (mGC3) uses the fact that in a nearly spherical potential the disruption of a satellite will produce a tidal stream approximately confined to a plane (see Figure 1) due to angular momentum conservation.

The mGC3 method consists in dividing the sky in a grid of all possible great circles, each cell being uniquely defined by its normal vector or pole \vec{L} . A pole count map is produced by counting the number of stars N_{stars} which have positions *and* velocities contained in each great circle cell, i.e. which fulfill the conditions

$$|\hat{L} \cdot \hat{r}| \leq \sin \theta \quad \text{and} \quad |\hat{L} \cdot \hat{v}| \leq \sin \theta, \quad (1)$$

where θ is a small angle that accounts for the finite width of the tidal stream (see Figure 2).

This represents an extension of the original GC3 method devised by Johnston et al. (1996), which uses only the positional criterium from equation 1. The addition of a velocity criterium, with respect to the original GC3 method, decreases the number of Milky Way (MW) stars contaminating each cell, increasing the ‘signal-to-noise’ ratio of a tidal stream by a factor of $\sim 10^2$.

An example of a pole count map for a simple distribution of stars is shown in Figure 2. The top plot in Figure 2 shows a sky projection of an arbitrary distribution of particles whose positions and velocities are coplanar (green great circle band). The bottom plot illustrates the resulting pole count map (the green band from the top figure is overlaid), where only poles orthogonal to the particle distribution are seen to have a signal.

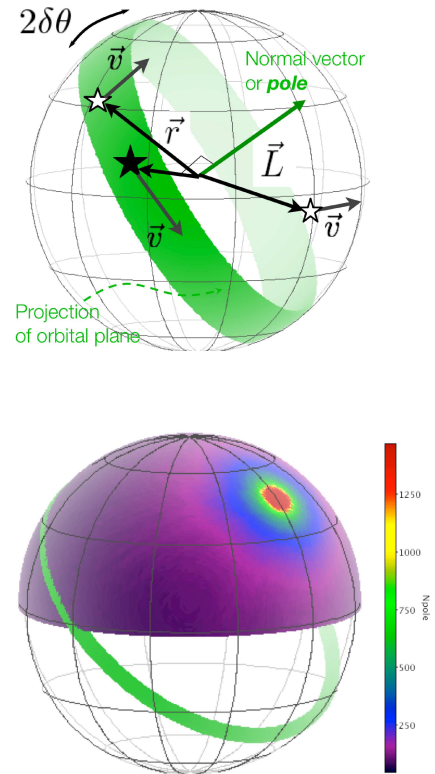


Fig. 2. (Top) Projected distribution of stars in a planar orbit (green band), and its normal or pole vector \vec{L} . Open stars represent background halo stars, the black filled star represents a stream star. (Bottom) Corresponding pole count map. The pole count excess due to the stars orbital plane is shown by the concentrated red peak. The color figure can be viewed online.

3. THE GAIA MOCK CATALOGUE

Testing a technique for finding substructure in the galactic halo, it is important to reproduce cor-

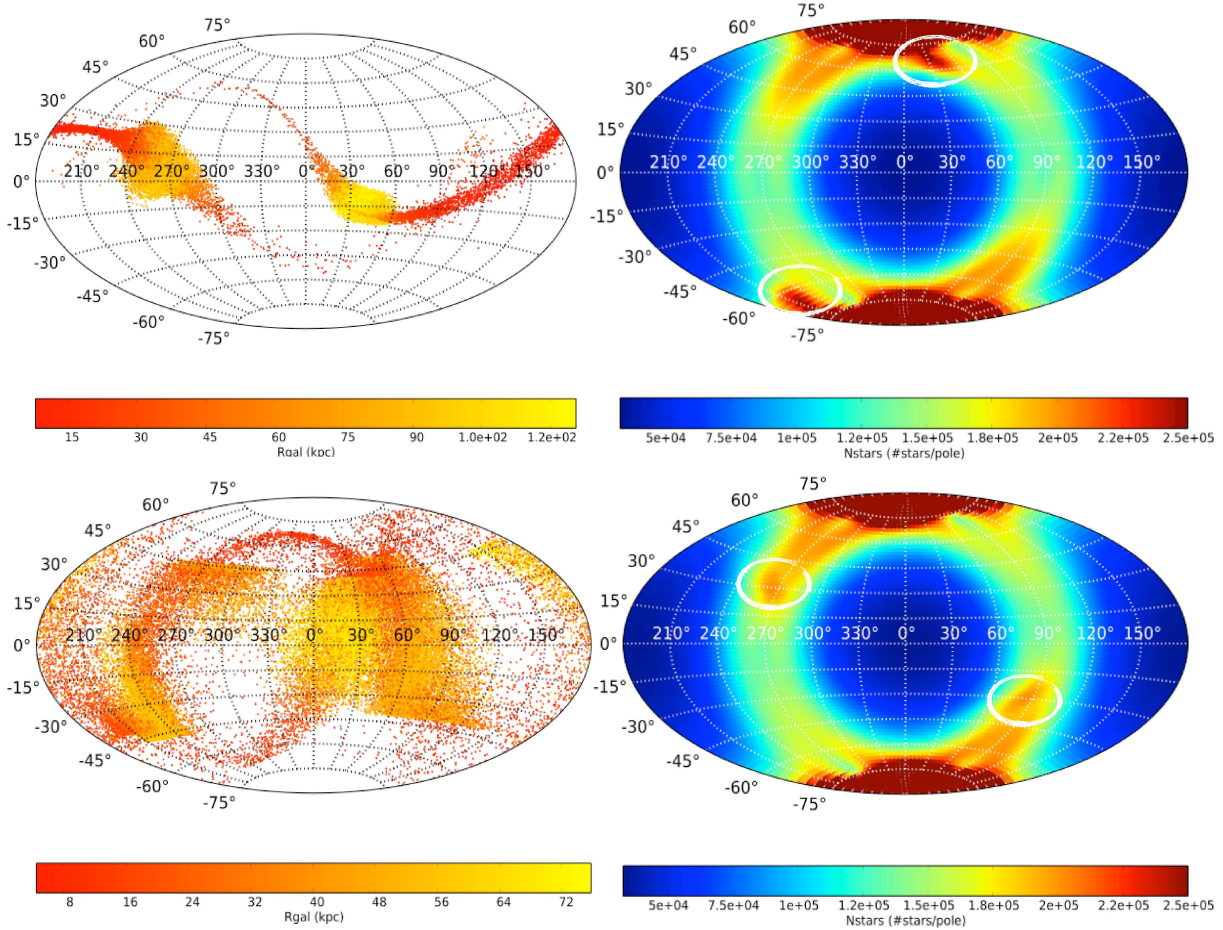


Fig. 3. Left: Aitoff projection plot of the spatial distribution of stream’s stars, with a color-scaling proportional to galactocentric distance R_{gal} . Right: mGC3 pole count maps corresponding to each stream (left) embedded in the mock Gaia catalogue of the galactic background, including observational errors. The top and bottom rows correspond to satellites S1 and S2 from Brown et al. (2005), with total luminosities $L_V \sim 5 \times 10^7 L_\odot$ and $L_V \sim 3.5 \times 10^8 L_\odot$, and dynamical ages of 8.5 Gyr and 9.1 Gyr respectively. The color figure can be viewed online.

rectly the ratio of the number of stars in the stream with respect to the roughly smooth galactic background. In order to do this, we used the mock Gaia catalogue from Brown, Velázquez, & Aguilar (2005). This mock catalogue simulates the observable astrometric and photometric properties for stars in the Milky Way, as will be observed by Gaia.

The Milky Way simulation takes into account the density profile, velocity dispersions and star formation histories (SFHs) for stars in the galactic halo, bulge and thin disk, each component being appropriately normalized to reproduce the total luminosity of each galactic component (see Brown et al. for details). The mock catalogue contains full phase-space information for a total of 3.4×10^8 simulated stars that will be observable with Gaia, excluding the region $|b| < 5^\circ$ in the I, IV galactic quadrants, in order

to avoid the denser parts of the disk towards the galactic center. The observational errors were simulated taking into account the expected dependences on ecliptic latitude, magnitude and color.

4. SATELLITE TIDAL STREAMS

To evaluate the efficiency of the mGC3 method we embedded the set of satellite streams from N-body simulations described in Brown et al. (2005) in the mock Gaia catalogue of the galactic background, also simulating the observational errors and completeness limits expected from Gaia (see Brown et al. 2005, for further details).

The N-body satellites were evolved for ~ 10 Gyr in a static galactic axisymmetric potential with a flattening $q_\Phi = 0.8$ (see Brown et al. 2005, for full details). The satellites’ total initial luminosity was

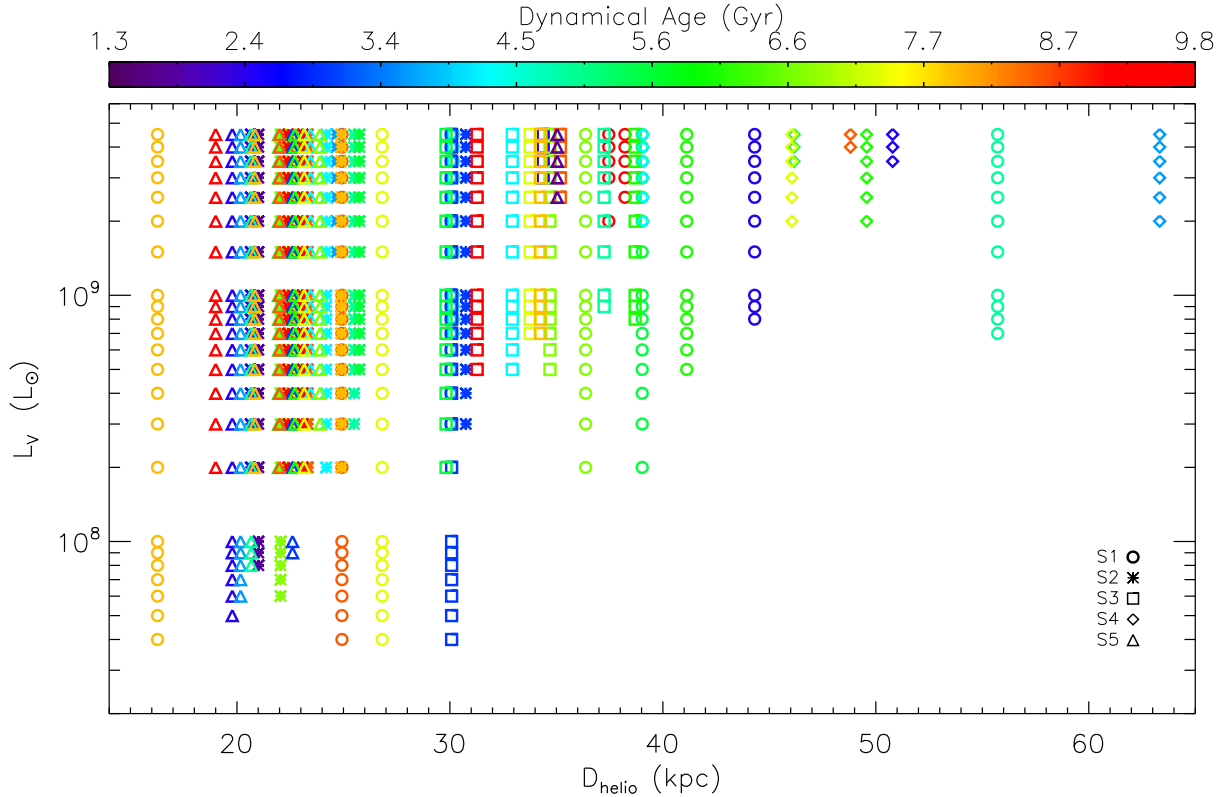


Fig. 4. Total luminosity L_V as a function of median heliocentric distance D_{helio} , for *recovered* satellites with a Carina-type SFH. The color scale is proportional to the dynamical age of the system. The different symbols correspond to the different satellites, as indicated in the legend at the lower left part of the plot. The color figure can be viewed online.

varied in the range $10^7 - 10^9 L_{\odot}$ and two different star formation histories were used: the halo-type, a 13 Gyr metal-poor ($[\text{Fe}/\text{H}] = -1.7$) burst resembling the galactic halo population; and the Carina-type, consisting of old, intermediate-age and young metal-poor populations with ages $\sim 13, 8, 3$ Gyr respectively, similar to the stellar population of the Carina dSph (Carigi & Hernández 2008).

Two examples of the tidal streams used are shown in Figure 3. The left-hand plots show the spatial distribution of each stream’s stars, in an Aitoff projection plot in galactocentric coordinates, using a color-scaling proportional to galactocentric distance R_{gal} . The right-hand plots are the mGC3 pole count maps corresponding to each stream embedded in the mock Gaia catalogue of the galactic background, including observational errors. The top row corresponds to satellite S1 from Brown et al. (2005), a dwarf galaxy with a total initial luminosity of $L_V \sim 5 \times 10^7 L_{\odot}$ and a Carina-type SFH, in an orbit with an inclination of 30° , an apocenter of 105 kpc and a pericenter of 8.5 kpc with a dynamical age of 8.45 Gyr. The bottom row corresponds to

satellite S2 from Brown et al. (2005), a dwarf galaxy with a total initial luminosity of $L_V \sim 3.5 \times 10^8 L_{\odot}$ and a halo-type SFH, in an orbit with an inclination of 45° , an apocenter of 60 kpc and a pericenter of 7 kpc, with a dynamical age of 9.1 Gyr.

The pole count maps in Figure 3 show the localized peaks (marked with white ovals) corresponding to each of the streams, superimposed on the smoothly varying background given by the galactic background (see Mateu et al. 2011, for details). Note that even for a highly disrupted tidal stream (S2, bottom row) the signature in the mGC3 pole count map is quite sharp and distinguishable from the galactic background.

Each satellite’s signature in a pole count map was recovered after subtracting a smoothed (unsharp masked) image, in which the value of each pixel corresponds to the median value in a fixed-size neighborhood. The ‘unsharp masking’ technique produces a subtracted image in which sharp features are enhanced, thanks to the removal of the softly varying component.

5. DETECTABILITY OF TIDAL STREAMS

We investigated mGC3's success rate as a function of initial satellite luminosity, star formation history, orbit and dynamical age. Figure 4 summarizes these results in a plot of initial satellite luminosity L_V as a function of D_{helio} , the median heliocentric distance of stars in the tidal stream at any given dynamical age, which is indicated by the color scaling. We use D_{helio} as an estimate of the typical distance to the bound core of the stellar stream, since the stream is naturally an extended structure. The plot includes only data for satellites with a Carina-type SFH and recovered in the 'unsharp masked' images as bona fide ($>4\sigma$) detections.

The plot in Figure 4 shows that all five satellites (S1–S5), which have stars observable by Gaia (meeting the requirement for parallax errors: $\Delta\varpi/\varpi \leq 30$ per cent), *can be recovered using mGC3* at different dynamical ages, for total luminosities in the range $10^8 - 10^9 L_\odot$ and even down to $4 - 5 \times 10^7 L_\odot$ for certain combinations of dynamical ages and orbital parameters. As can be seen in the figure, dynamically old tidal streams ($\gtrsim 7$ Gyr) can be recovered even for large distances up to ~ 30 – 45 kpc for luminosities larger than $\sim 10^8 L_\odot$, and even down to luminosities of a few $\times 10^7 L_\odot$ for smaller distances ($\lesssim 25$ kpc). Dynamically younger systems can be detected in a wider range of luminosities and distances. Results for satellites with an older, and therefore fainter, halo-type SFH (not shown in Figure 4) can be recovered down to luminosities $L_V \sim 7 - 8 \times 10^7 L_\odot$ for some combinations of orbital parameters and dynamical ages (see Mateu et al. 2011).

6. CONCLUSIONS

In this contribution we have presented the following results.

- The use of a velocity criterion in the mGC3 method increases the 'contrast' of stream signals with respect to galactic background stars in pole count maps.
- We have tested the ability of the modified GC3 method to recover tidal streams with different total luminosities and SFHs, with a data set that realistically simulates both the observational errors and the observable numbers of galactic and stream stars.
- We find that satellites with luminosities in the range $10^8 L_\odot - 10^9 L_\odot$ can be recovered, even for events as dynamically old as ~ 7 – 10 Gyr up to distances of ~ 30 – 40 kpc, and at larger distances for satellites with brighter/younger populations.
- Even satellites as faint as $L_V \sim 4 - 5 \times 10^7 L_\odot$ can be recovered for certain combinations of dynamical ages and orbits.
- Detection limits found here for the mGC3 method are only *lower limit estimations* since we used only (simulated) stars with positive trigonometric parallaxes. Gaia will also provide accurate *photometric* parallaxes for a much larger and more distant sample of stars.

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