Detecting Halo Streams with GAIA

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Abstract. We investigate what the proposed ESA astrometric satellite GAIA will reveal by observing the halo of the Milky Way. Specifically, we look for halo streams which are the signatures left by the merging/accretion events experienced by a typical galaxy like the Milky Way. We run numerical simulations of the disruption of satellite galaxies in a Galactic potential to generate artificial GAIA halo catalogs. We recover the streams by searching for peaks in angular momentum space.

1. Introduction

GAIA is a short-listed candidate for an ESA cornerstone mission provisionally scheduled for launch in 2009. It will provide precise astrometry ($<10\mu$as in parallax and $<10\mu$as yr$^{-1}$ in proper motion at $V \sim 15$, increasing to 0.2 mas yr$^{-1}$ at $V \sim 20$) and multicolour photometry, for all 1.3 billion objects to $V \sim 20$, and radial velocities with accuracies of a few km s$^{-1}$ for most stars brighter than $V \sim 17$, so that full six-dimensional phase-space information will be available. GAIA will thereby provide a very large and statistically reliable sample of stars, from which the questions concerning the origin and evolution of the Galaxy may finally be answered. In this contribution we address what GAIA may tell us about the history and formation of the stellar halo of the Milky Way.

Hierarchical theories of structure formation in the Universe propose that galaxies are the result of mergers and accretion of smaller building blocks. Such events would leave fossil signatures in the present day components of the Milky Way, and in particular in its stellar halo. When a satellite galaxy is disrupted, it leaves trails of stars along its orbit, so that when all accretion events are superimposed, a spheroidal component may be produced. Recent observations have shown that indeed considerable structure is still present in Milky Way’s halo, indicating that accretion events have had some role in its formation history (e.g. Majewski this volume).

There are several methods for detecting moving groups. The Great Circle Counts method (G3C) proposed by Johnston, Hernquist & Bolte (1996) uses the position on the sky, and employs the fact that satellites in orbits that probe only the outer (spherical) halo conserve the orientation of their plane of motion, thereby leaving their debris along great circles on the sky, if observed from the Galactic center (see also Johnston, this volume). The methods used in the Solar neighborhood for detection of disk moving groups and open clusters use also proper motions (and sometimes parallax), and assume that all the stars belonging to the same system have the same velocity vector (e.g. Hoogerwerf &
Aguilar 1998; de Bruijne 1998). Lynden-Bell & Lynden-Bell’s method (1995) needs the position on the sky and the radial velocity, and has been used, for example, to link globular clusters which lie on the same plane to some of the (disrupted) dwarf companions of our Galaxy (see also Lynden-Bell, this volume).

The applicability of the abovementioned methods is questionable in the inner parts of the halo. In this regime, the Galactic potential is strongly axisymmetric so that the debris does not remain on a fixed plane, the situation where G3C works. As an example in Figure 1 we show a sky projection of a satellite 8 Gyr after disruption: no strong angular correlations are visible. On the other hand, even though the velocity dispersions in a stellar stream do decrease with time, and therefore, very strong correlations are to be expected (see Helmi & White this volume), in the inner halo strong phase-mixing takes place. Since the superposition of streams can give a velocity dispersion as high as 200 km s\(^{-1}\), it would be rather difficult to detect satellite debris if only velocity information is used. Clearly, we need to identify where the clustering that is characteristic of a satellite manifests itself in the debris that we observe after many galactic orbits.

![Figure 1. Galactocentric sky projection for one of our experiments.](image)

A satellite can be considered an ensemble of particles with very similar integrals of motion (energy, angular momentum) as shown in Figure 2. Since these are conserved quantities, or evolve only slightly, this initial clumping should be present even after the system has phase-mixed completely. Therefore, the space of integrals or adiabatic invariants is the natural space to look for the substructure produced by an accretion event.

We use angular momentum as a measure of the lumpiness in the stellar halo. Even though it is not fully conserved for an axisymmetric potential (only \(L_z\) is), it evolves preserving a certain degree of coherence. Since the computation of the angular momentum does not involve any detailed knowledge of the Galactic potential, the method is very powerful in identifying substructure if 6-D information is available. Moreover, the number of clumps detected in this way will represent well the total number of accretion/merging events, since unlike other
methods which are only local, it singles out all the stars from a given accreted object, independently of how different their phases and velocities might be.

2. Putting the method to work

To generate an artificial GAIA catalog for the Galaxy we need to include the accretion events, which are the substructure that we will be searching for, and a smooth phase-space distribution of particles for the disk and the bulge. We describe here how to generate such a data set, focusing on the accretion events and their detection. We also discuss briefly the effect of the smooth component.

For the accreted component we use numerical simulations of the disruption of satellite galaxies with masses $10^7 - 10^8 \, M_\odot$, initial dispersions $3 - 8 \, \text{km s}^{-1}$ and sizes $1 - 2 \, \text{kpc}$. Their orbital periods are in the range $0.5 - 1.5 \, \text{Gyr}$, and their pericentres lie in the inner halo ($< 10 \, \text{kpc}$). We assume that the $10^5$ particles, which represent each $10^7 - 10^8 \, M_\odot$ satellite, are KIII or MIII stars, since this is roughly the expected number of giants of this spectral type in a $10^9 \, \text{Gyr}$ old object of such mass. This is to consider only stars that are bright enough to be observable from the Sun. We convolve the positions and velocities of the particles obtained from the simulations with the expected measurement errors, given in Table 1. If a star-particle is too faint to have a measurable parallax it is left out of the analysis. For a KIII star this corresponds to $V \sim 21$.

Figure 3 shows the ‘observed’ angular momentum distribution of the particles that are left in the catalog after the previously described analysis. For

| $V$ | $\sigma_\pi$ | $\sigma_\mu$ |
|-----|-------------|-------------|
| 10  | 4.05        | 2.43        |
| 13  | 5.01        | 3.01        |
| 14  | 7.41        | 4.44        |
| 15  | 11.5        | 6.86        |
| 16  | 18.2        | 10.9        |
| 17  | 29.9        | 17.9        |
| 18  | 51.6        | 30.9        |
| 19  | 96.8        | 58.0        |
| 20  | 202.6       | 121.3       |
| 21  | 609.3       | 365.0       |
Figure 3. Density contours for the distribution of the ‘accreted’ stars in angular momentum space, after convolution with observational errors, for our 10 satellites at 13.5 Gyr after infall. We use a bin of 100 kpc km/s in the $L_z$-direction and of 200 kpc km/s in the $L$-direction. In this plot, the disk is located at $L = L_z$, and the bulge dominates the region of $L < 2000$ kpc km s$^{-1}$.

In this plot, the disk is located at $L = L_z$, and the bulge dominates the region of $L < 2000$ kpc km s$^{-1}$. The disk can also be identified easily in the $L_z - L$ plane as a narrow fringe located at $L = L_z$. On the other hand, the bulge shares similar spatial and kinematical properties with the stellar halo. In the $L_z - L$ plane it is located in the $L < 2000$ kpc km s$^{-1}$ region. One way of suppressing most of its contribution would be to separate bulge and halo with a metallicity criterion (Minniti 1996). Nevertheless, we may want to analyze the bulge in more detail,

comparison see the right panel of Figure 2 which represents the initial distribution, prior to disruption and without any measurement errors. The lumps remain coherent and hence the events can be recovered. The success of the method is largely due to the full use of what characterizes a satellite in phase-space at all times: its clumping in the adiabatic invariants space. Secondly, the accuracy of GAIA practically makes the initial and final distributions (i.e. after error convolution) nearly indistinguishable. It follows that we should be able to easily detect any accreted satellite in the high angular momentum part ($L > 2000$ kpc km s$^{-1}$) of the $L_z - L$ plane. In the lower regions of that diagram we may find superposition of events, so that a more sophisticated analysis (not just the use of contour plots) will be needed. Moreover, the inclusion of the smooth distribution due to the Galactic disk and bulge will also require a deeper analysis, since the number of stars in these components is much larger than that of the stellar halo. For example, a large part of the disk can be suppressed by removing from the catalog all stars located within 1 kpc from the Galactic plane.
since hierarchical theories predict that bulges may also form by accretion and merging events.

3. Discussion

From Figure 3 we conclude that the method is successful in detecting the structure left by the accretion events.

One of the limitations of the method is the need of the 6-D information which constrains the volume around the Galactic center that we can probe with the GAIA measurements to $\sim 20$ kpc (in the Sun’s direction), however most of the halo stars are within that volume. As discussed in the previous section, we may not be able to resolve all accreted events. For example, if the number of disrupted satellites is very large the chances of superposition will be larger. However we can add extra dimensions using the conservation of energy with a better constrained Galactic potential (see Zhao et al. this volume). We may also zoom in on those overlapping regions, to look for smaller scale structure, and use as well velocity correlations.

The evolution of the Galactic potential may be the most crucial simplification in our analysis. In hierarchical cosmologies the number of objects that form a galaxy like our own is in the range of 5-20, with comparable masses. The process of formation is likely to be very violent and the potential is surely not static, quite probably not axisymmetric, and therefore the initial clumping of the system may not be reflected in clumping in angular momentum space. However, if this happened during the first few Gyrs, any object falling later, ought to have perceived a fairly static (or adiabatically changing) Galaxy, and then our method would still be of use. This probably covers masses up to several times $10^9 M_\odot$.

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