Building up the Stellar Halo of the Milky Way

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Abstract. We study numerical simulations of satellite galaxy disruption in a potential resembling that of the Milky Way. Our goal is to assess whether a merger origin for the stellar halo would leave observable fossil structure in the phase-space distribution of nearby stars. We show how mixing of disrupted satellites can be quantified using a coarse-grained entropy. Although after 10 billion years few obvious asymmetries remain in the distribution of particles in configuration space, strong correlations are still present in velocity space. We briefly describe how we can understand these effects based on the conservation of fine-grained phase-space density in an action-angle formalism. We also discuss the implications of our results on the known properties of the stellar halo.

1. Introduction

Currently popular theories of structure formation in the Universe postulate that structure grows through the amplification by gravitational forces of initially small density fluctuations (see White 1996 for a review). Depending on the characteristics of the spectrum of fluctuations, small objects can be the first to collapse; they then merge to form progressively larger systems giving rise to the complex structure we observe today. In this hierarchical structure formation scenario our Galaxy, as a typical galaxy, should also have been formed in part by merging and accretion of smaller galaxies, or ‘building blocks’. These events should be imprinted in some of its present-day components, presumably as residual structure. For example, when a galaxy is disrupted it leaves trails of stars along its orbit. These could be superposed in a spheroidal component such as a stellar halo. In fact, numerous observations suggest substructure in the halo of the Galaxy (see Majewski in this volume). In this paper, we attempt to describe what the signatures of different accretion events should be if indeed our Galaxy formed as envisaged in current theories. Should this merging history be observed in star counts, kinematic or abundance surveys of the Galaxy? How prominent or not would these substructures be? How well-mixed are the stars that made up these progenitors? What can we say about the properties of the accreted satellites from the observations we have today?
2. Simulations and Results

To tackle the questions we just posed we carry out N-body simulations of accretion of satellite galaxies, where we represent the Milky Way by a fixed, rigid potential and the satellite by a collection of particles. The self-gravity of the satellite is modelled by a monopole term as in White (1983).

The Galactic potential is represented by two components: a disk described by a Miyamoto-Nagai potential,

$$\Phi_{\text{disk}} = -\frac{GM_{\text{disk}}}{\sqrt{R^2 + (a + \sqrt{z^2 + b^2})^2}},$$

(1)

where $M_{\text{disk}} = 10^{11} M_\odot$, $a = 6.5 \text{kpc}$, $b = 0.26 \text{kpc}$, and a dark halo with a logarithmic potential,

$$\Phi_{\text{halo}} = v_{\text{halo}}^2 \ln(r^2 + d^2),$$

(2)

with $d = 12 \text{kpc}$ and $v_{\text{halo}} = 131.5 \text{km s}^{-1}$. The initial density distribution of the satellite is given by a Plummer profile

$$\rho(r) = \frac{\rho_0}{(r^2 + r_0^2)^{5/2}},$$

(3)

with $\rho_0 = 3M/4\pi r_0^3$, $M = 10^7 M_\odot$ being the initial mass of the satellite and $r_0 = 0.53 \text{kpc}$ its scale length. Its one-dimensional internal velocity dispersion is $2.9 \text{km s}^{-1}$. We run several simulations which differ in their orbital parameters, which span a range in radial periods from 0.5 to 1.3 Gyr, and have an apocentre to pericentric distance ratio of 5 to 10 (fairly radial orbits). We have also imposed that the orbits pass close to the solar circle to compare the results of the experiments with the known properties of the stellar halo of the Milky Way. In all cases the satellite was represented by $10^5$ particles of equal mass. We find that the satellites become completely unbound after, at most, three pericentric passages.

2.1. Analysis of the simulations: Structure in phase-space

One process that will tend to erase any macroscopic correlation between the particles, making more difficult the detection of satellite debris, is phase-mixing. To quantify it we use the coarse-grained entropy defined as:

$$S[f] = -\int \bar{f} \ln \bar{f} d^3 x d^3 v,$$

(4)

where $\bar{f}$ is the coarse-grained distribution function, that is, the average of the actual distribution function $f$ over small cells in phase-space. One of the interesting properties of $\bar{f}$ is that it decreases as the system becomes phase-mixed. Therefore, $S[f]$ is expected to increase with time, as shown for our simulations in Figure 1. In practice, we replace the integral by a sum over cells, and $\bar{f}$ by the fraction of particles in each cell.

The spatial properties of the debris can be studied by plotting isodensity surfaces. These surfaces are indicative of how spread in its available configuration volume the system is, or equivalently how advanced the disruption is. We
Figure 1. Evolution of the entropy of the system for the different experiments, as a function of time. Orbits which go deeper into the potential, and have the shortest periods, show the most advanced state of mixing, which is not complete after a Hubble time.

find that for the region of parameter space probed, these volumes are almost completely filled after a Hubble time. In terms of the spatial distribution of the particles on the plane of the sky (see Helmi, Zhao and de Zeeuw, this volume, their Figure 1) we do not find any strong correlations, contrary to what Johnston, Hernquist and Bolte (1996) find in their simulations of accretion in the outer halo. We can understand this in terms of the short time scales and the strong flattening characteristic of the inner parts of our Galaxy. The maximum densities of such debris are three to four orders of magnitude lower than the initial density of their progenitors, roughly comparable to the local density of the stellar halo.

In order to reflect what observers can do in surveys of the local halo, in Figure 2 we plot the kinematical properties of stars inside a box of 3 kpc on a side in different locations along the orbit. Notice the strong correlations between the different components of the velocity vector inside any given box, and, in particular, the large velocity range in each component when close to the Galactic centre. This shows that the debris can appear kinematically hot. This is the result of a combination of multiple streams within a given box (clearly visible in Figure 2) and strong gradients along each stream. At a given point along any particular stream the dispersions are usually very small.

2.2. What sets the characteristic scales?

Because the disruption of the satellite occurs very early in its history, it can be considered as an ensemble of test particles during most of its evolution. One
of the distinguishing properties of this ensemble is that it initially had a very high density in phase-space, and by virtue of Liouville’s theorem, this is true at all times. At later times, however, this is no longer reflected by a strong concentration in configuration space. Since the behaviour of a dynamical system is particularly simple in action-angle variables:

\[
\Phi = \Phi_i + \Omega(J)t, \\
J = J_i = \text{constant}.
\]

we can find the evolution of the distribution function in the following way. We know the distribution function at the initial time \(f(x_i, v_i)\). By a transformation of coordinates we may write it as a function of action-angle variables at that initial time: \(f(\Phi_i, J_i)\). Eqs. (5) then give the distribution function at a later time \(t\) in action-angle variables. If we now transform locally from \((\Phi, J)\) back to \((x, v)\), we obtain the distribution function, and thereby the velocity dispersions and the density behaviour, in the region of interest. In action-angle variables the system expands along three directions and contracts along the remaining three. This is directly associated with the equations of motion. Any initial dispersion in the angles can only increase (Eqs. (5)), so that the system becomes a very elongated ellipsoid in phase-space as time passes by. The conservation of phase-space density (Liouville’s theorem) then forces the other directions to shrink. This is reflected in the projection onto observable space. It is possible to show (see Helmi & White 1998 for all the details) that the velocity dispersions decrease on the average with time, and so the volume density also decreases with time as the system expands in the spatial directions. For example in the spherical case.
the dispersions and the central density behave as

\[
\frac{\sigma(v_\varphi)}{\sigma_i(v_\varphi)} \propto \frac{t_0}{t}, \quad \frac{\sigma(v_\rho)}{\sigma_i(v_\rho)} \propto \frac{t_0}{t}, \quad \frac{\rho}{\rho_i} \propto \left(\frac{t_0}{t}\right)^2.
\]

The velocity dispersion in the direction transverse to the plane of motion (θ) is constant, except for periodic variations due to the orbital phase. In the axisymmetric case, there no longer is a preferred orientation, so that also in the θ-direction the velocity dispersion decreases, and therefore the density decreases as \(t^{-3}\).

3. Discussion

Our results suggest that fossil structure from an accretion event which took place at any time during the the history of the Milky Way should be visible in velocity space. A stream of stars is, most of the time, fairly cold. However, in particular in the inner parts of the Galaxy, it is quite likely to find more than one stream from any particular disrupted satellite in a small region in configuration space. In that case, the apparent velocity dispersions can be much larger, although constrained by the initial dispersions in the integrals of motion. Majewski, Munn & Hawley (1994) reported the discovery of a moving group near the NGP (for details see Majewski, this volume) with large velocity dispersions (greater than 30 km s\(^{-1}\)), and with a mean motion very different from that of the other stars in the field. If we are to take these stars as satellite debris, we will have to invoke a multistream structure in order to explain their kinematics. Indeed, there is some evidence of substructure in their distribution of angular momenta. This is to be expected if indeed there are multiple streams. With this in mind, we can use our simulations and analytic results to estimate the mass of the progenitor using the simulations, and estimates for its initial size and velocity dispersions. We find: \(M \sim 10^9 M_\odot\), \(R \sim 6\) kpc and \(\sigma(v) \sim 28\) km s\(^{-1}\).

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