The Role of Accretion in Forming the Galactic Halo

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Abstract. If the Galaxy formed hierarchically through the accretion of smaller satellite galaxies we might hope to find signatures of this in the halo’s phase-space distribution. I review theoretical ideas about what form these signatures should take, concentrating in particular on the characteristics of debris from the tidal disruption of satellites less than the size of the Large Magellanic Clouds and at distances greater than 10 kpc. Under these circumstances, tidal debris can remain aligned in streams of stars close to the satellite’s original orbit for the lifetime of the Galaxy and we can understand the evolution of its structure analytically. This understanding has many applications to observations and I will discuss a few examples: reconstructing the properties of a long-dead satellite from its debris; measuring the mass loss rate from Galactic satellites through the density of extra-tidal stars; and using observations of motions of tidal stream stars to measure the mass and size of the Milky Way.

1. Introduction

Theories describing the formation of the Galactic halo can be viewed as variations on or combinations of two scenarios. Based on the kinematics of metal-poor halo field stars [Eggen, Lynden-Bell & Sandage (1962)] proposed that the halo formed during the rapid collapse of an initially uniform primordial density fluctuation. In contrast, to account for the lack of metallicity gradient in the outer halo, [Searle & Zinn (1978)] proposed that it was formed gradually through the merging of many sub-galactic sized lumps. On somewhat larger scales, fluctuations in the Cosmic Microwave Background radiation and observations of Large Scale Structure are most closely matched by simulations of Cold Dark Matter dominated Universes, in which galaxies form hierarchically from the accretion of smaller satellites. Observations of individual galactic halos also show substructure that could be signatures of these disruption events — both around our own Galaxy (see Majewski 1998 in this volume for a review) and around external galaxies (e.g. Shang et al 1998). Hence, current theoretical ideas and observations support a view that satellite accretion has played some role in the formation of the Galaxy.

The next decade promises significant progress in building a global picture of halo structure and substructure, with upcoming satellite missions providing accurate phase-space coordinates for individual stars in the inner and outer halo. NASA’s Space Interferometric Mission (SIM), scheduled for 2006, is a pointed instrument that will detect stars as faint as 20th magnitude with accuracies of
a few $\mu$as. ESA’s Global Astrometric Interferometer for Astrophysics (GAIA) will survey more than a billion stars across the entire sky with an astrometric precision of $\leq 10\mu$as. This represents an improvement over results obtained with the HIPPARCOS satellite by a factor of about a thousand in accuracy and more than a million in the volume sampled. Such a data set should allow us to understand what fraction of the halo formed in situ and what fraction was later added either through minor mergers (where the mass of the infalling body is a few percent of the mass of the Milky Way) or satellite accretion (where the satellite has a mass less than a few tenths of a percent of the mass of the Milky Way).

With sufficient computing power, one can imagine interpreting substructure in the halo using fully self consistent simulations of galaxy formation and subsequent merging and accretion events in a cosmological setting. Unfortunately, with current hardware and software it is barely feasible to resolve the mass scales of even the largest of the Milky Way’s current population of satellites ($10^6 - 10^9 M_\odot$) with more than a few hundred particles. Hence, in this review rather than trying to place halo formation in a cosmological context I will instead focus on understanding what could be the observable signatures of the disruption of a small satellite ($\leq 10^{-3} M_{MW}$ where $M_{MW}$ is the mass of the Milky Way) in the outer halo ($\geq 10$ kpc) of our Galaxy. Although such events may contribute only a small fraction of the Milky Way’s total mass, they are nevertheless interesting because these mass and orbit parameters: (i) give timescales for debris dispersal longer than the age of the Galaxy so signatures from destruction of such primordial satellites should still be visible in the halo field star population; (ii) are comparable to those of today’s satellites, so we can apply the results to features in the halo that could be associated with the current satellite population; and (iii) result in the close alignment of debris with a single orbit which has interesting implications for the use of debris to measure the Galactic potential. For explorations of the disruption of small objects in the inner halo see Helmi & White (1998) and Harding et al. (1998) in this volume, and for a review of minor and major mergers see Barnes (1996).

In §2 I will discuss how debris from the disruption of a satellite in orbit around the Milky Way disperses and in §3 I will review how this understanding can be applied to interpret observations of substructure in the halo. I will summarize these ideas and future prospects in this field in §4.

2. Debris Dynamics

2.1. Simulations

One approach to understanding how debris from satellite disruptions disperses is to use numerical simulations. Figure 1 summarizes the evolution of a satellite in one such simulation, where the satellite’s self-gravity was followed using a basis-function-expansion code written by Hernquist & Ostriker (1992) and the Milky Way’s potential was modeled with bulge, disk and halo components represented by static, analytic functions (see Johnston, Spergel & Hernquist 1995 for more details of the technique). The satellite’s particles were initially distributed as a Plummer model, with a mass of $10^8 M_\odot$ and scale length of 0.55 kpc, and it was evolved along an orbit that oscillated between peri- and apo-centric distances of...
Figure 1. Evolution of debris from a satellite disrupting while orbiting around the Milky Way. Each box is centered on the Galaxy and is 176 kpc on a side. The frames are equally spaced over 4.5 Gyrs and the particles are color-coded with the time they were torn from the satellite. The orbit is overlaid as the solid curve in the middle box. See text for parameters.

30kpc and 55kpc, with a radial time period of 1 Gyr. The mass and orbit for this satellite were chosen to be comparable to the dwarf spheroidal satellites we see in orbit around the Milky Way. However, its physical scale was deliberately set so that it would lose a significant amount of mass during course of the simulation.
The panels in Figure 1 are equally spaced over 4.5 Gyrs. In the middle panel the orbit of the satellite has been overlaid to emphasize that the tidal debris spreads predominantly along the orbit of the satellite during this time and hence that this alignment should last for the lifetime of the Galaxy. Since most of the mass loss from the satellite occurs at pericenter (where the tidal field of the Milky Way is strongest), the particles have been coded in greyscale: the light particles were lost during the first and third pericentric passages, and the dark particles were lost during the second and fourth. Note that these sets form distinct populations. The evolution of each population can be described separately using the formalism outlined in the next section.

2.2. Analytic representation of debris dispersal in spherical potentials

Tremaine (1993) outlines a simple physical picture of debris dispersal, which I summarize below. In all equations the first equality gives the expression for the properties of a tidal streamer in a general spherical potential \( \Phi(\mathbf{R}) \) and the second equality is for the specific case of a logarithmic potential

\[
\Phi = v_{\text{circ}}^2 \log(R),
\]

as might be appropriate for the halo of a galaxy with a flat rotation curve and circular velocity \( v_{\text{circ}} \).

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**Figure 2.** Characteristics of satellite disruption. Upper panel shows a cartoon of the spatial distribution and the lower panel is the corresponding distribution in scaled energies (see text)
Figure 2 is a cartoon representation of the characteristics seen in the simulation. The satellite is limited by the Milky Way’s tidal field to a physical scale given by its tidal radius

$$r_{\text{tide}} = \left( \frac{m}{M} \right)^{1/3} R = \left( \frac{Gm}{v_{\text{circ}}^{2} R} \right)^{1/3} R$$

(2)

where $m$ is the mass of the satellite system, $R$ is the distance between the parent and satellite and $M$ is the mass of the parent system enclosed within this radius (King 1962). The stars escaping from the satellite which lose (gain) energy move more tightly (less tightly) bound orbits and form leading (trailing) streams of debris along its orbit. The energy scale over which these particles are distributed is given by

$$\epsilon = r_{\text{tide}} \frac{d\Phi}{dR} = \left( \frac{Gm}{v_{\text{circ}}^{2} R} \right)^{1/3} v_{\text{circ}}^{2}.$$  

(3)

This is larger than the internal energy of the satellite by a factor $(M/m)^{2/3}$ and smaller than the satellite’s orbital energy by a factor $(m/M)^{1/3}$. When the energies of debris particles in simulations of accretion with a wide variety of satellite and orbit parameters are scaled by the factor given in equation (3) their distributions are found all found to have the form illustrated in the bottom panel of Figure 2.

Figure 3. Left hand panel: energies of debris particles at the end of the simulations illustrated in Figure 1 plotted against their angular distance from the satellite. Right hand panel: radial velocity of debris particles plotted against distance from the parent galaxy. The closed curve in this panel is the locus of the satellite’s orbit. The solid squares in both panels show the semi-analytic predictions for the properties of the tidal streamers.

We can approximately predict the spatial distribution of debris lost from their energy distribution by taking the time period of an orbit perturbed by $\Delta E$
to be
\[ T(E + \Delta E) = \tau(\Delta E)T(E), \]  
(4)
where \( T(E) \) is the time period of a circular orbit of energy \( E \) and \( \tau \) is a dimensionless function, simply given by \( \tau(\Delta E) = \exp(\Delta E / v_{\text{circ}}^2) \) for the logarithmic potential (i.e. ignoring the weak dependence of time periods on angular momentum). Then if a satellite on an orbit of energy \( E \) loses some mass at time \( t = 0 \) and angular position \( \Psi = 0 \), and moves to position \( \Psi(t) \) at time \( t \) later, mass lost with energy \( (E + \Delta E) \) will be at angular position \( \Psi(t/\tau) \). For full details of this approach, see Johnston (1998). The success of this simple picture is illustrated in the left hand panel of Figure 3, which plots the orbital energies of debris particles relative to the satellite’s orbital energy against angle \( \Psi \) along the orbit at the end of the simulation shown in Figure 4, with the particles again coded in greyscale with their escape time. Note that few particles have energies \( |\Delta E| < \epsilon \) since this is the energy needed to escape from the satellite. Note also that there is a monotonic trend along each streamer of particle energy with angle with a small dispersion around it, confirming that the difference in the orbital energies is primarily responsible for the debris spreading. The dark squares overlaid on the particles show the predictions of the semi-analytic method for the positions of the streamers in this plane. The number density along the streamers can be modeled with similar success by using the intrinsic distribution of debris in orbital energy seen in the simulations (Johnston 1998).

Inspection of the simulations also shows that the full phase-space position of debris of relative energy \( \Delta E \) can be represented by adopting the velocity of the unperturbed orbit at the same azimuthal phase, but offsetting the streamer in distance by
\[ \Delta R = \frac{\Delta E}{d\Phi/dR}. \]  
(5)
The right-hand panel of Figure 3 shows the final positions of particles in the position-radial velocity plane with the semi-analytic model again overlaid to demonstrate this.

Once the debris spreads to cover several oscillations in azimuthal and radial phase the simple approximation to its phase-space structure outlined above, which is based only on its energy distribution, will break down. An exact representation would incorporate all the integrals of motion, but once the streamers become spatially indistinct the value of treating them individually becomes less obvious (see Helmi & White 1998 for discussion).

2.3. Generalizations and Limitations

The discussion in the previous section was formulated and tested for spherical satellites with \( (m/M)^{1/3} \ll 1 \) on bound, non-radial orbits in the outer halo, which was represented by near-spherical, smooth and static potentials. In this section I sketch some limits of this approach.

Small satellite disruption in the inner halo: In the simulations discussed so far, the dominant source of phase-mixing is that due to the spreading of debris in one dimension along the orbit itself, only a few orbital phases are filled during the lifetime of the Galaxy and the signatures of disruption remain distinct in all
phase-space dimensions. In contrast, in the inner halo, Helmi & White (1998) find that debris from satellite disruption spreads to cover many orbital phases within a Galactic lifetime, and that the maximum volume of phase-space filled (in infinite time) can be found by simply integrating the satellite’s orbit. In addition, they demonstrate that signatures of disruption can remain clear in velocity-space even when the streamers are spatially indistinct (see also Harding et al 1998).

**Satellite geometry:** If a disk rather than spherical satellite disrupts, similar principles should apply for the scale at which disruption occurs and for the way in which debris spreads. However, the distribution in orbital energies and angular momenta will depend on the internal phase-space structure of the satellite and this would be reflected in the details of the density distribution along the tidal streamers.

**Parent galaxy geometry:** Although the discussion in the previous two sections used examples of disruption in parent galaxy potentials that were dominated by spherical components I have found similar alignment of debris with the satellite’s orbit in a small number of test simulations of bound, non-radial orbits in oblate and triaxial potentials. One can imagine that this alignment would break down if the debris spread into regions of phase space where the orbit type abruptly changed (e.g. from a loop to a box orbit) or became chaotic. In the case of a disk galaxy like our Milky Way, this is likely to be a concern only in the inner regions where the potential will be most highly flattened by the disk or triaxial due to the influence of the bar.

**Minor mergers and plunging orbits:** There are many cases of simulations reported in the literature where the one-dimensional spread of debris along a single orbit is not seen (e.g. Hernquist & Quinn 1988). In minor mergers or for disruptions along radial orbits this is because the condition \((m/M)^{1/3} \ll 1\) is not satisfied and the debris is released with a large range in orbital energies, inclinations and phases. Hence, it quickly spreads to fill two or more spatial dimensions and cannot be modeled effectively by considering phase-mixing along a single orbit.

**Time dependence and smoothness of parent galaxy potential:** In all of the above cases I have considered the evolution of a cloud of test particles phase-mixing along orbits in smooth, static potentials. This ignores changes in the satellite’s orbit due to dynamical friction, the self-gravity in the debris and evolution of tidal streamer’s due to a lumpy or time-dependent parent galaxy potential. The first of these simplifications is justified in the range of satellite and orbital parameters considered and the second can be demonstrated to be unimportant (Johnston 1998). However, the last of these simplifications should be noted as a concern — potential fluctuations would affect both the streamer and satellite orbits.

3. Applications
3.1. Modeling substructure in our own halo

Reconstructing Properties of Long-Dead Satellites Using Conserved Quantities

The longevity of the alignment of tidal streamers suggests that properties of primordial satellites could be reconstructed by searching for objects associated with a single orbit. This idea was first applied to the two-dimensional projected distribution of satellites by Lynden-Bell (1976) and Kunkel & Demers (1977), who both noted that several of the dwarf spheroidals lie close to the Great Circle defined by the Large Magellanic Clouds and the Magellanic Stream. Later studies suggested possible associations of globular clusters with each other and with the larger satellites (Lin & Richer, 1992, Majewski, 1994, Fusi-Pecci et al., 1995, Lynden-Bell & Lynden-Bell, 1995, Majewski, 1994, Fusi-Pecci et al., 1995, Lynden-Bell & Lynden-Bell, 1995) and Johnston, Hernquist & Bolte (1996) applied the same principles to develop a general algorithm that searches for Great Circle alignments in stellar data sets. Irwin & Totten (1998) have recently found perhaps the most compelling example of satellite debris seen in projection using this latter method — a set of carbon stars aligned with the direction of elongation of the Sagittarius dwarf galaxy.

The two-dimensional approach implicitly assumes that the halo potential is only mildly oblate and that debris will lie close to a plane (or Great Circle in projection on the sky). Lynden-Bell & Lynden-Bell (1995) show how, with the assumption of a specific form for the Galactic potential, the addition of distance and radial velocity measurements can provide further tests of object association by requiring that they have similar energy and angular momentum. The accurate proper motion measurements with the upcoming SIM and GAIA satellite missions (see §1) will allow the measurement of angular momenta directly in the inner halo, which can alone serve as a fair discriminant of streamers from the field population (see Helmi, Zhao & de Zeeuw 1998).

![Figure 4](image.png)

**Figure 4.** The solid line shows the number of giant branch stars per kpc along the line of sight in a degree-squared patch of sky for a smooth halo distribution. Each solid square shows the equivalent density of debris left from the disruption of a satellite at that distance 10 Gyrs ago.
Finding Local Features  The methods in the previous section all used conserved quantities to discriminate likely members of streamers over large areas of the sky. On smaller (square-degree) scales, phase-space substructures in the form of moving groups of stars in the inner halo have already been detected (see Majewski, Hawley & Munn 1996 for a review and Helmi & White 1998 for interpretation). The first results from two surveys to identify and measure distances to and radial velocities of giant stars to far greater depths in the halo also show significant substructure (Majewski 1998, Harding et al. 1998). Figure 4 illustrates the power of such studies. The solid curve shows an estimate for the number of giant stars per square degree per kpc along the line of sight if the outer halo followed the smooth $\rho \propto r^{-3.5}$ density profile measured in the inner halo (Freeman 1996). Each of the solid squares show the density of debris from a satellite disrupted 10 Gyrs ago at the given distance from the Galactic center, estimated using the scalings given in §2.2. The figure suggests that stellar debris from such an event should be easily identified above the smooth background with the addition of distance measurements alone.

3.2. Measuring Mass Loss Rates from Galactic Satellites

Figure 5. Annularly averaged number surface density from a simulation of satellite disruption “observed” from the viewpoint of the center of the Galaxy after several Gyrs. The closed (open) symbols show the profile recovered if only bound (all) stars are considered. The dashed line shows the density of “extra-tidal” stars (i.e. open symbols) predicted from our understanding of debris dynamics.

Number count profiles of many Galactic and some extra-galactic satellite systems show evidence for associated stars beyond the cut-off in density that is identified as the point of tidal limitation (e.g. Irwin & Hatzidimitriou 1995, Grillmair et al. 1995). These “extra-tidal” stars are assumed to be debris lost from the satellite due to heating or stripping by the Galactic tidal field or (in the case of globular clusters) evaporation of stars over the tidal boundary. Figure 5 shows the annularly averaged number surface density from a simulation of satellite disruption “observed” from the viewpoint of the center of the Galaxy after several Gyrs. The closed (open) symbols show the profile recovered if only bound (all) stars are considered. Clearly there is a break in the open symbols.
at the radius where the analysis becomes dominated by unbound stars (approximately indicated by the vertical dotted line) confirming the interpretation of “extra-tidal” stars as debris. Johnston, Sigurdsson & Hernquist (1998) apply the same principles outlined in §2.2 to estimate the expected density of the tidal debris beyond the tidal radius from the mass-loss rate seen in the simulation and this estimate is overlaid in dashed lines on the profile shown in Figure 5. This method reproduces the extra-tidal features in all simulations tested with similar success. This suggests that our understanding of debris dynamics can be used to measure the mass loss rate from a Galactic satellite using the observed density of extra-tidal stars. When tested on the simulations, this approach recovered the mass loss rate to within a factor of two. When applied to observations it can be used to provide constraints on dynamical models of individual satellites and to directly measure the current destruction rate of the Galactic satellite system.

### 3.3. Measuring Potentials

The alignment of tidal streams along a single orbit make them uniquely useful as probes of the Galactic potential, an idea that has been noted by a number of authors (Lynden-Bell 1982; Kuhn, Smith & Hawley 1996; Grillmair 1998). By assuming that several of the dwarf spheroidal satellites are tidal debris, Lynden-Bell (1982) was able to obtain an estimate of the mass of the Milky Way. Similarly, if the Magellanic Stream consists of gas tidally stripped from the Large and Small Magellanic Clouds, it can be used to constrain the potential (Murai & Fujimoto 1980; Lin & Lynden-Bell 1982). While these results are not definitive measurements owing to the controversial nature of the Magellanic Stream (Moore & Davis 1994) and association of the dwarf spheroidals, they demonstrate the power of this approach.

The growing observational evidence for the existence of stellar tidal streamers in the halo (Majewski 1998), coupled with the prospect of highly accurate measurements of stellar proper motions in the outer halo using the SIM and GAIA satellite missions to be launched within the next decade motivates a re-examination of this idea. Assuming measurements of just 100 stars in a tidal streamer associated with a known Galactic satellite could be made with these upcoming missions, Johnston, Zhao, Spergel & Hernquist (1998) found that the circular velocity and axis ratios of the halo could be recovered to within a few percent - an order of magnitude improvement over previous methods (see Zhao, Johnston, Spergel & Hernquist 1998 in this volume for a summary of the method).

### 4. Summary

In this review I have looked at the characteristics of signatures we would expect in the outer halo’s phase-space distribution from the accretion of small satellites. Under these circumstances, tidal streamers from the disruption of the satellite are long-lived, the rate of debris dispersal is well-understood and their structure can be modeled using simple physical arguments. We can use the properties of any streamers observed in the halo to reconstruct the characteristics of the primordial object from which they came. If they are associated with a particular satellite, we can use their density to measure the rate at which the satellite...
is currently disrupting. Finally, even if the halo is dominated by a smooth component and accretion of small satellites is unimportant, a small number of stars in tidal streamers can be used to measure the Galactic potential with far greater accuracy than the same number in the random population.

The next decade promises to be an exciting one for progress in this field. Preliminary results from current observational surveys hint that the outer halo is indeed far from smooth, and future satellite missions promise to extend these local samples to build a truly global picture of Milky Way structure and substructure, with accurate measurements of all phase-space coordinates in the inner halo and five of the six phase-space dimensions further out (the error in the measurement of the distance $D$ to an object is $\sim (D/20\text{ kpc})^2$). With the prospect of applying their results to these observational data sets, theorists can look beyond the classic static models of Milky Way structure, and beyond the simple picture of debris dispersal from small satellites I have outlined in this review and hope to constrain a fully self-consistent picture of Galaxy formation and evolution.

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