WANDERING STARS: AN ORIGIN OF ESCAPED POPULATIONS

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1. INTRODUCTION

One of the triumphs of the last decade is orders of magnitude increase in the numbers of stars cataloged by large sky surveys such as the Sloan Digital Sky Survey and the Two Micron All Sky Survey. These catalogs contain significant samples of stars out to ~100 kpc from the center of the Galaxy, allowing these regions to be probed through number counts to far lower surface brightness than previously possible and resulting in the discovery of numerous new dwarf satellite galaxies (e.g., Willman et al. 2005; Belokurov et al. 2006), as well as tidal tails from dwarf galaxies possibly disrupted long ago (e.g., Majewski et al. 2003; Belokurov et al. 2005).

We move from this decade of large sky surveys into a decade of continual all-sky surveying with the introduction of Pan-STARRS (see Kaiser 2004) and the prospect of the Large Synoptic Survey Telescope (LSST; see Ivezic 2007). These surveys will be sensitive on smaller scales to explain the existence of ICL around less massive, looser clusters and galaxy groups (Arnaboldi 2004), as well as diffuse stellar halos around individual galaxies (Bullock & Johnston 2005). Thus, stellar halos and the ICL can be thought of as testaments to galactic interactions during the epochs of galaxy and cluster formation.

We explore whether dynamical interactions could plausibly lead to stars beyond the virial radii of the parent galaxy, group, or cluster, and, if so, what the existence of such a population might tell us about the nature of hierarchical structure formation. Spergel & Hernquist (1992) have already shown that N-body simulations of mergers of massive galaxies can give rise to unbound particles that form a Gaussian tail to the energy distribution, in agreement with a statistical mechanical description of violent relaxation. Here, we develop a simple description of interactions that allows us to illustrate how the size of the escaped population should depend on the mass ratio of the parent and satellite. In Section 2, we establish that a tidal impulse at perigalacticon is a viable path for stars from satellite dwarf galaxies to escape from the combined dark matter potentials of the parent and satellite galaxies. In Section 3, we use restricted three-body simulations to test the mechanism described in Section 2 and then analyze N-body results to establish trends, and quantitative expectations for the escaping population. In Section 4, we discuss the implications of our results for future surveys of giant stars, CN, supernovae and high-velocity stars (HVSs). In Section 5, we summarize our conclusions.

1.4. Mechanism for Escape

Consider a satellite orbiting in a parent potential \( \Phi(r) \), at radius \( r \) from the center of the parent, moving with velocity \( \mathbf{v} \), along an orbit of energy \( E = \frac{1}{2} \mathbf{v} \cdot \mathbf{v} + \Phi(r) \). As the satellite orbits, a
star at position x relative to the center will experience a slightly different acceleration due to the parent than the satellite as a whole. In the impulsive regime, the resultant relative velocity change between the star and the satellite can be approximated as \( \Delta v \sim \Delta a_{\text{peri}} t_{\text{enc}} \) where \( t_{\text{enc}} = r_{\text{peri}} / v_{\text{peri}} \) is the duration of an encounter of pericentric distance \( r_{\text{peri}} \) and speed \( v_{\text{peri}} \), and \( \Delta a_{\text{peri}} \) is the difference in acceleration experienced by the satellite and star at pericenter. Expanding \( \Delta v \) in powers of \( x \) we have

\[
\Delta v \sim a_{\text{peri}} t_{\text{enc}} = (x \cdot \nabla) \nabla \Phi(r) t_{\text{enc}}
\]

\[
\sim -GM_{\text{peri}} \left( \frac{x}{|r_{\text{peri}}|^3} - \frac{3}{5} \frac{r_{\text{peri}} (x \cdot r_{\text{peri}})}{|r_{\text{peri}}|^5} \right) t_{\text{enc}},
\]

where \( M_{\text{peri}} \) is the enclosed mass of the parent at pericenter. The first and second terms in Equation (1) are responsible for stretching along \( r \) and compression perpendicular to \( r \), respectively.

This impulsive velocity change corresponds to a change in orbital energy

\[
\Delta E = v \cdot \Delta v + \frac{(\Delta v)^2}{2}.
\]

When summed over all stars in the entire satellite, the first term in Equation (2) typically vanishes due to symmetry, and the last term represents the dynamical heating. In contrast, for an individual star, the last term is usually negligible compared to the first. The maximum increase in orbital energy will be for stars barely bound to (i.e., at large \( r_s = |x| \)) and trailing the satellite along its orbit (i.e., where the direction of the impulse \( \Delta v \) is aligned with the orbital motion), where

\[
\Delta v \sim \frac{2GM_{\text{peri}}}{r_3_{\text{peri}}} r_s t_{\text{enc}} \sim \frac{2GM_{\text{peri}}}{r_2_{\text{peri}}} v_{\text{peri}}.
\]

Such a trailing star could move to an orbit that escapes entirely from the combined parent-satellite system if \( \Delta E \sim v_{\text{peri}} \Delta v > |E| \) or

\[
\Delta v > \frac{|E|}{v_{\text{peri}}},
\]

In combination, Equations (4) and (3) yield a constraint on the minimum extent of stars in the satellite system for an escaping population to be produced: \( r_s > r_{\text{s, min}} \) where

\[
r_{\text{s, min}} = \frac{|E|}{2GM_{\text{peri}} / r_{\text{peri}}}.
\]

We examine whether Equation (4) will be satisfied for any realistic galactic encounters by estimating \( r_{\text{s, min}} \) for orbits in a Milky Way-like parent halo that follows a Navarro–Frenk–White (NFW) potential of virial mass \( m_{\text{vir}} = 1.4 \times 10^{12} M_\odot \), virial radius of \( r_{\text{vir}} = 273 \) kpc, and characteristic radius \( r_c = 20.7 \) kpc. The functional form of the NFW is

\[
m(r) = m_c \left( \log \left( \frac{r + r_c}{r_c} \right) - \frac{r}{r + r_c} \right),
\]

where the mass within distance \( r \) is \( m(r) \) and \( m_c = 4\pi \delta_c \rho_c r_c^3 \) is the mass within the characteristic radius (Navarro et al. 1994). Figure 1 shows numerically solved contours of \( r_{\text{s, min}} \) as a function of circularity, \( J_{\text{frac}} = J_{\text{frac}} \), and fractional binding energy parameter, \( \eta = \frac{\frac{\nu}{\text{peri}}}{\nu} \), for a satellite orbit of energy \( E \) and angular momentum \( J \). \( J_{\text{circ}} \) and \( R_{\text{circ}} \) are the angular momentum and radius of a circular orbit of the same energy \( E \). Satellite orbits become more loosely bound with increasing \( \eta \) and more eccentric with decreasing \( J_{\text{frac}} \). From Figure 1, \( r_{\text{s, min}} \) depends weakly on binding energy, but strongly on orbital eccentricity. For any \( \eta \) or \( J_{\text{frac}} \), more massive (i.e., of greater stellar extent) satellites are likely to create a greater number of E/W stars than a smaller satellite. A satellite on an eccentric orbit will contribute more stars than the same satellite on a less eccentric orbit. The lowest contours on Figure 1 overlap with the typical extent of stars in Local Group dwarf galaxies. As we observe satellites which meet criteria in Figure 1 today, logically, this is indeed a plausible mechanism for ejecting stars from a Milky Way-sized halo during its formation epoch.

Analogous calculations performed for an NFW potential on cluster scales, with \( M_{\text{vir}} = 1 \times 10^{14} M_\odot \), show contours of similar shape but more than a factor of 10 increase in amplitude. While these scales are much greater than the sizes of typical galactic disks, these results do allow that the same mechanism may liberate the most loosely bound parts of galaxies (the stellar halos of spirals and the outer edges of ellipticals) from the cluster.

3. ILLUSTRATIONS OF ESCAPE

3.1. Restricted Three-body Simulations

A restricted three-body code follows the orbits of stars as a dark-matter satellite orbit its parent galaxy. Stars may (“escaped” stars, E) or may not (“wandering” stars, W) become energetically unbound from the parent-satellite system, but the two classes are likely to be observationally indistinguishable; a wandering star can take a jaunt beyond the virial radius that lasts for a significant fraction of the age of the universe. Note, the intention in this section is not to estimate the size of the E/W population, but to confirm the predicted escape mechanism (Section 2).

Our restricted three-body model consists of two orbiting, analytical, non-volting NFW dark matter halos, and 10,000 massless “tracer” particles which represent stars around the smaller of the two halos (the “satellite”). Simulations are performed in two pieces—orbits for interacting NFW halos are calculated first, then tracer particles are run in the changing potential. The code uses leapfrog integration. Orbital precision
is ensured by comparing results for the same parameter sets calculated with orders of magnitude change in time resolution.

The Milky Way-like (as described in Section 2) parent NFW is identical in all runs. Simulations run with satellites of various characteristic masses \( (m_s, \text{ of } 10\%, 1\%, \text{ and } 0.1\% \text{ of the parent}) \) and scale radii \( (r_c, \text{ of } 7 \text{ kpc, } 3 \text{ kpc, and } 1 \text{ kpc}) \), drawn from distributions seen at \( z = 0 \) in cosmological simulations: Bullock et al. (2001) are placed on orbits with various \( R_{\text{circ}} \) (130 kpc, 200 kpc) and \( \eta \) (0.05, 0.1, 0.5). Parent and satellite dark matter halos are truncated at their respective tidal radii at initial apogalacticon.

Since we are interested in generating escaping stars, massless particles are not chosen to reproduce a fixed density distribution, but rather to explore regions of phase space that are most likely to be stripped. They are placed randomly with a spatially uniform distribution around the satellite, out to its tidal radius. Their velocities are initially spatially isotropic, with amplitudes forming an uniform energy distribution up to the escape energy of the satellite at a given radius \( E_{\text{esc}, \text{sat}}(r) \), i.e., the vast majority of stars should escape from the satellite. We eliminate particles unbound within the first 1/10 of the orbit; they are uninteresting for analysis of evolution near pericenter.

Figure 2 is an example satellite from these runs, with an \( m_s = 10\% \text{ that of the parent, on an orbit with } R_{\text{circ}} = 200 \text{ kpc and } \eta = 0.05. \) The satellite is mostly stripped of its initially uniform cloud of test particles (gray) by pericenter. Test particles that are ahead of the satellite along its orbit at the first pericenter form a cloud around the center of the parent potential by second apocenter. In contrast, black crosses highlight the positions of the subset of particles that form the E/W population—defined as those that are ejected and remain outside the virial radius of the system for more than 2 Gyr. While this subset follows the same isotropic distribution as the non-escapers at apocenter, they clearly lag the satellite along its orbit at pericenter. Every run which generates wandering stars demonstrates this behavior, confirming the dynamical picture proposed in Section 2; the E/W population can be ejected by an impulsive velocity change at pericenter aligned with the orbital motion.

### 3.2. N-Body Simulation

While the restricted three-body models successfully illustrate the mechanism for generating E/W stars, they are of limited use in assessing the size of this population or trends in progenitor properties for four reasons: satellites do not self-consistently lose mass as they orbit, star particles are not embedded deep within their host dark matter halos, parent potentials do not grow, and satellite’s orbits do not evolve due to dynamical friction with the parent. (Note that none of these effects would invalidate our description of the formation mechanism.)

We turn our attention to cosmological N-body simulations (Bullock & Johnston 2005) of satellite accretion, where mass loss from the satellite is modeled self-consistently, stars are distributed more realistically, an estimate of dynamical friction is explicitly included, and parent potentials grow analytically. The original aim of these simulations was to examine the formation of the stellar halo of the Milky Way. The set includes 11 stellar halo models, each formed from the superposition of simulations of individual satellite acccretions, whose masses, accretion times, and orbits were chosen at random from cosmologically motivated distributions. Gravitational influence of the parent galaxy is calculated from analytic functions which represent disk, bulge, and dark matter halo components and that grow smoothly over time (tied to a randomly generated accretion history) to form a Milky Way type galaxy today. Dark matter in each satellite is represented by \( 10^{5} \) equal-mass particles, with positions and velocities initially chosen to follow an equilibrium NFW distribution. Masses and scales of these NFW halos are drawn from those seen in fully self-consistent cosmological simulations of structure formation. Stars are “painted-on” by assigning a variable mass-to-light ratio to each dark matter particle in such a way that they follow an equilibrium King model, whose total luminosity, spatial, and velocity scales are normalized to match observed scaling relations of Local Group dwarf galaxies.

Our 11 stellar halo models all contain an E/W population with an average of 5.5% (and ranging between 2.5% and 10%) of the stars beyond the virial radius of the host today. Since these models only follow the stellar halo component of the Galaxy (~ \( 10^{6} M_\odot \) in stars), this represents a much smaller fraction of the total light of the Galaxy—of order 0.05%. This is a lower limit to the E/W population since it does not include those that might be contributed from the parent galaxy, or from disk components of satellites during more major mergers.

We ask what types of interactions are responsible for the E/W population in these simulations. In Figure 3, we look at the fraction of stars defined as E/W, averaged over all 11 stellar halo models as a function of satellite mass and orbital properties. The solid line plots the cumulative fraction of E/W stars (i.e., the number of E/Ws divided by the total number of stars falling in to the parent) from all satellites less than a given mass. The dot-dashed/dotted/dashed lines are the subset of satellites with \( J_{\text{frac}} < 0.25/0.5/0.75 \) — the orbit distribution for these satellites was originally nearly uniform in \( J_{\text{frac}} \). This figure confirms the trends anticipated in Section 2; the bulk of the E/W population is produced by (1) larger mass satellites since they are intrinsically more extended and more stars satisfy the criterion \( r_s > r_{s, \text{min}} \); and (2) satellites on more eccentric orbits with smaller pericenters that minimize \( r_{s, \text{min}} \). In particular, by comparing the solid and dotted lines we see that for all masses, much more than 50% of the population is produced from objects...
on the most eccentric orbits. Also, at the very lowest masses the dot-dashed line converges with the total: smaller satellites need to be on increasingly eccentric orbits in order to contribute to the E/W population.

4. DISCUSSION

Our results indicate the plausible existence of a population of isolated stars thrown out beyond the virial radii of Milky Way-sized dark matter halos. We expect that most of this population was generated during the epoch of structure formation on various scales. While these results should be confirmed by simulations of structures forming in a fully self-consistent cosmological context, our estimates suggest a lower limit of 0.05% of stars could be in this population of E/W stars, and this number could be revised significantly upward once the contribution from the disk component in equal-mass mergers is included.

There are promising avenues for detecting such a population. Shara (2006) has pointed out that near-future all-sky, repeated surveys should be able to map the distribution of CN out to the Virgo cluster. Assuming an E/W population of ~10% (from the levels of ICL) he calculates a detection rate of hundreds to thousands during the first few years of LSST for a typical stellar population. Such surveys would also be sensitive to the young HVS population, in part because they are easy to select photometrically (i.e., from unusual blue colors and faint magnitudes at high Galactic latitude; see Brown et al. 2006). This young population is thought to originate from multiple-star encounters with the Galactic Center black hole—though Abadi et al. (2009) have shown using N-body simulations that such speeds can be produced in satellite/parent galaxy encounters, presumably by the mechanism we describe analytically here. Systematic surveys of the stellar halo velocity distribution of the older (redder) population are just now producing additional results (Kollmeier et al. 2009) and could provide an interesting additional limit on the E/W population.

5. CONCLUSIONS

We have outlined how tidal interactions can eject stars which are loosely bound to a satellite galaxy to beyond the virial radius of the satellite’s parent. We determined that more massive satellites contribute the most to this escaped (entirely unbound from the satellite/parent system) or wandering (bound, but traveling beyond two virial radii for more than ~Gyr) population of stars, as do satellites on highly radial orbits. The majority of this population of stars originated during the epoch of galaxy formation, when large interacting satellites were more frequently infalling on radial orbits, approximately from a redshift of around 4–3. If this is indeed the case, we expect an old, uniform (to first order) population of escaped and wandering stars to exist beyond two virial radii for more than a few Gyr. We have outlined how tidal interactions can eject stars which are loosely bound to a satellite galaxy to beyond the virial radius of the satellite’s parent. We determined that more massive satellites contribute the most to this escaped (entirely unbound from the satellite/parent system) or wandering (bound, but traveling beyond two virial radii for more than ~Gyr) population of stars, as do satellites on highly radial orbits. The majority of this population of stars originated during the epoch of galaxy formation, when large interacting satellites were more frequently infalling on radial orbits, approximately from a redshift of around 4–3. If this is indeed the case, we expect an old, uniform (to first order) population of escaped and wandering stars to exist beyond two virial radii for more than ~Gyr.

“Not all those that wander are lost.”—J. R. R. Tolkien

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