

SUBSTRUCTURE AND TIDAL DEBRIS IN LOCAL GALAXIES: MODELS AND OBSERVATIONS

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ABSTRACT

One of the generic predictions of modern cosmological models is that large galaxies should have experienced many mergers with smaller galaxies at some point in their past. Debris from such encounters will leave spatially distinct substructure in the stellar haloes of nearby galaxies, detectable for a few orbital periods after the final merger. In the case of the Milky Way, kinematic data from surveys such as RAVE and satellite missions such as Gaia will allow us to probe much more of the merger history, and to connect the properties of the stellar halo with those of local dwarf galaxies. To estimate what these programmes may discover, we review current observations of minor mergers in nearby galaxies, and compare these with predictions from a semi-analytic model of galaxy formation.

Key words: Galaxy: formation, halo; Galaxies: dwarf, interactions; Dark matter.

1. INTRODUCTION: THE ROLE OF MERGERS IN CURRENT COSMOLOGICAL MODELS

In cosmological models consistent with current observations of the cosmic microwave background (CMB), large-scale structure, and estimates of the mean baryon density, roughly 85% of the matter in the universe is non-baryonic cold dark matter (CDM). Small fluctuations in the initial distribution of CDM are known to lead, via gravitational instability, to the formation of dense, gravitationally bound structures at later times. These dark matter ‘haloes’ should reach masses and densities sufficient to allow gas to cool and condense within them, thereby permitting efficient and sustained star formation, at redshifts of ~ 20 or higher. Thus they represent a natural structural framework within which visible galaxies can form, from the earliest epoch onwards.

A generic prediction of cosmological models based on CDM is that the dark matter haloes around galaxies continue to grow through accretion and mergers with smaller haloes, right up to the present day. The merger rate

for galaxy haloes reaches a peak at a redshift of $z \sim 1-3$, however, and more recent mergers between galaxy haloes and their associated galaxies will typically be minor ones, adding little to the total mass of the larger component. The average merger in the local universe may consist of a small, low surface-brightness dwarf galaxy being stretched out and disrupted over the course of several orbits around its parent. The only direct signature of such an event would be minor fluctuations in the surface brightness of the stellar halo around the larger galaxy, lasting for a few orbital periods (Johnston et al. 2001). Thus, while low-redshift mergers provide an important empirical test of the CDM framework, they may be extremely difficult to detect in practice.

In the case of the Milky Way, stellar kinematics provide a unique opportunity to study the merger history in much greater detail, identifying debris from older or more minor mergers thanks to its clustering in phase-space (Tremaine 1993; Johnston 1998; Helmi & White 1999). Ground-based radial velocity surveys such as RAVE¹ and future astrometric missions such as Gaia² will explore a completely new range of parameter space in the merger history of this one particular galaxy, and should thereby provide an important link between local stellar populations and the properties of small galaxies forming at the highest redshifts. To explore the potential of these programmes, we will review current observations of debris from minor mergers in external galaxies, and attempt to extend these results to older or smaller satellites using a semi-analytic model of galaxy formation.

2. OBSERVED STREAMS IN NEARBY GALAXIES

Given their theoretical significance, there has been much recent interest in detecting ongoing minor mergers in local galaxies. The most spectacular discoveries of this kind were those made in our own galaxy and in M31. In 1994, Ibata et al. announced the discovery of the Sagittarius Dwarf, a small system in the process of being disrupted by the Milky Way, whose tidal debris is now spread out over a large fraction of the sky. More recently, an equally spectacular tidal stream was discovered

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¹<http://www.aip.de/RAVE>

²<http://www.rssd.esa.int/Gaia>

around M31 (Ibata et al. 2001; McConnachie et al. 2003), and there is growing evidence for another stream in the plane of the Milky Way (e.g., Newberg et al. 2002; Ibata et al. 2003). The LMC-SMC system can also be considered an ongoing minor merger, since it has already experienced strong tidal effects due to its proximity to the Milky Way (e.g., Harris & Zaritsky 2004), and will eventually merge with the Galaxy as dynamical friction acts on its orbit.

Much of the tidal debris detected locally has a very low surface brightness, and would be difficult or impossible to detect in distant systems. Nonetheless, there has been some progress in detecting debris around galaxies outside the Local Group. Early work by Malin & Hadly (1997) found faint features in the stellar haloes of several galaxies, including M83, M104 and NGC2855, some or all of which may be tidal debris from minor mergers. A clear example of a tidal stream was discovered around the edge-on spiral NGC5907 by Shang et al. (1998), and the nearby active galaxy Centaurus A has a tidal feature of young blue stars, possibly associated with the recent merger that triggered its central activity (Peng et al. 2002). These results were reviewed and discussed recently by Pohlen et al. (2004), who also report newly detected streams in four other galaxies. Their systematic search around 80 edge-on disc galaxies yielded only one of these examples, however, suggesting the incidence of obvious streams is low. More recently, Forbes et al. (2003) have reported the serendipitous discovery of a dwarf in the process of disruption, with well-defined tidal streams, in the background of a Hubble Advanced Camera image of the Tadpole system. These discoveries confirm that minor mergers are still taking place, but suggest that it may be hard to obtain a large sample to compare with theoretical models. Finally, we note that stellar streams are not the only tracer of minor mergers in external galaxies; others include distinct populations of globular clusters, gas or dust lanes in early-type galaxies, and kinematic or structural anomalies. The theoretical interpretation of these features is less straightforward, however, as their properties may depend more on the long-term response of the main system (e.g., via AGN or starbursts) than on the nature of the initial perturber.

3. THE UNRESOLVED PROBLEM OF DWARF GALAXY FORMATION

Given this growing body of information on minor mergers and tidal streams, it is worth estimating how often these events are expected to occur in current galaxy formation models. In recent years several groups have begun to study the formation of the stellar halo in its full cosmological context (e.g., Bullock et al. 2001; Bekki & Chiba 2001; Brook et al. 2004; Bullock & Johnston 2004). The problem is not as straightforward as it seems, however. The properties of the stellar halo will depend on when and how the satellites that merged into it first formed. While simulations of structure formation have now converged on the properties of dark matter structures on the relevant scales, it is still not clear how these structures are populated with visible stars.

It has been known since the early days of CDM that galaxy formation must be systematically less efficient in smaller haloes, since the luminosity function of field galaxies flattens below some magnitude, whereas the halo mass function should be close to a power law over the corresponding range (e.g., Kauffmann et al. 1993). More recently, high-resolution simulations by Klypin et al. (1999) and Moore et al. (1999) have demonstrated that this discrepancy is even more dramatic for satellites within systems like the Local Group. Using internal velocities to relate dark matter sub-haloes to visible systems, they showed that down to the scale of the smallest systems, there should be almost 100 times more sub-haloes around the Milky Way than there are detected satellites. Subsequently, there has been much discussion of whether dwarf galaxies populate a small subset of all sub-haloes over a wide range of mass/internal circular velocity, as proposed by Moore et al. (1999), or whether they correspond to kinematically cold stellar cores within the most massive sub-haloes, as suggested by Stoehr et al. (2002) and Hayashi et al. (2003).

The second of these solutions is appealing, as it could indicate that there is a single characteristic halo mass below which star formation ceases. This solution is strongly disfavoured, however, if not ruled out, by the strong spatial clustering of the satellites of the Milky Way. The best estimates of the mass of the Milky Way put its virial radius somewhere around 300 kpc. If this is the case, then two-thirds of its satellites lie within the central third of the halo. The chance of this happening if satellites populated only the most massive haloes is less than 1% (Taylor et al. 2004). The disagreement in the cumulative radial distributions is shown in Figure 1, where we compare the average results for the dozen most massive satellites from each of a large set of semi-analytic models of halo substructure, generated using the method outlined in Taylor & Babul (2004a,b,c) (solid line + dotted 99% contours) with the distribution for the satellites of the Milky Way (upper line & triangles). Thus at least some of the satellites must reside in smaller haloes.

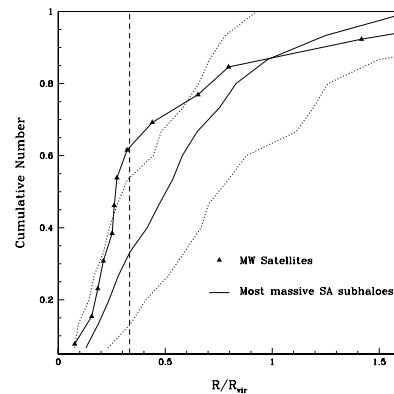


Figure 1. The cumulative radial distribution of visible satellites around the Milky Way (upper line/triangles), compared with the predicted distribution of the most massive sub-haloes (lower solid line, with dotted 99% contours).

There may be additional clues to the origin of the local dwarfs in their kinematics, which appear very different from those of randomly selected sub-haloes. In Figure 2, for instance, we show how the positions and radial velocities of known satellites (points with error bars) compare with the distribution of massive haloes taken from a large set of semi-analytic haloes. There is a clear mis-match between the two distributions in projection along either axis.

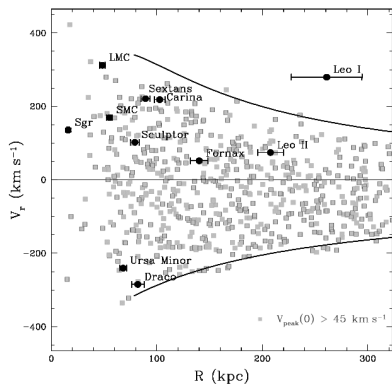


Figure 2. Radial velocity versus position for the satellites of the Milky Way (points with error bars) and the most massive sub-haloes from a series of semi-analytic haloes (smaller symbols).

One possible explanation, both for the spatial clustering and for the observed velocity distribution, is that most of the dwarfs are old, and that the lower cutoff to dwarf formation increases with time. In particular, Kravtsov et al. (2004) have produced a detailed model of dwarf formation where this occurs naturally, through a combination of internal and external feedback. In the next section we will consider a simplified version of this model and discuss its implications for stream formation.

4. A SEMI-ANALYTIC MODEL OF STREAM FORMATION

Given the complexity of modelling dwarf galaxy formation self-consistently, it is useful to construct a simplified semi-analytic model of the process, to get a preliminary estimate of how often minor mergers with dwarf satellites would have occurred in a system like the Milky Way. Our model is based on the semi-analytic model of halo formation presented in (Taylor & Babul 2004a,b,c), which predicts the numbers, orbits, internal properties and dynamical evolution of dark matter sub-haloes within a galaxy halo. To make predictions about visible satellites, we will suppose that stars form preferentially in sub-haloes with deeper potential wells, but also that the lower threshold to this process increases with time, such that the some of the largest sub-haloes around the Milky Way have never formed stars. Specifically, we choose a time-varying threshold in peak circular velocity of the form $V_p > V_{p,0} (1+z)^{-\alpha}$. Sub-haloes that exceed this threshold at any time before they merge with the main halo are

assumed to host visible dwarf galaxies. The two parameters in this model can be adjusted to give the right total number and spatial distribution of surviving satellites at the present-day.

Having identified which systems form stars, we can then estimate when stellar material will be stripped from them and added to the stellar halo. We assume the stars within a given sub-halo are restricted to its central region, in keeping with the observed sizes of dwarf galaxies, and consequently that tidal stripping does not produce visible streams until a system has lost most of its original dark matter. Considering the stellar-to-total mass ratios of larger galaxies, we set a mass-loss threshold at 83%, and refer to systems that have lost less than this fraction of their original mass as ‘surviving satellites’, and those that have lost more as ‘tidal streams’. Systems that lose more than 99% of their mass may become completely unbound (Taylor & Babul 2004a), so we refer to them as ‘disrupted’ in what follows.

The distribution of stripped material from systems containing stars is shown in Figure 3, for one particular semi-analytic halo. The debris is plotted at the point where it was first stripped off, to highlight the underlying orbital structure. Over time this material will be heated and phase-mixed, producing a smoother final halo. The colours in the figure indicate the age at which the stripped system first merged with the main halo. There is a strong age gradient in the final system, with ancient mergers contributing most of the material within the solar radius, while more recent mergers add streams to the outer halo.

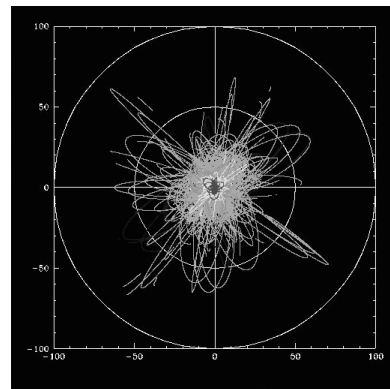


Figure 3. Tidal debris from merging satellites in a semi-analytic model halo, plotted at the point where it was first stripped. The material is colour-coded by age, the central material being systematically older. The figure is in the plane of the disc and the scale is in kpc.

5. RESULTS: PREDICTED STREAM PROPERTIES

Using the model outlined above, we have generated streams in a large set of model haloes. We find that we can produce an average of ten ‘surviving’ satellites per halo, roughly the number known to-date for the Milky Way, by setting $V_{p,0} = 135 \text{ km s}^{-1}$ and $\alpha = 2/3$ in

the expression given above. With this choice of parameters, our model predicts ~ 8 ‘tidal streams’ (i.e., heavily stripped stellar systems) per halo, and more than 100 disrupted dwarf galaxies, as well as 15 that have merged directly into the centre of the main galaxy on very radial orbits. Figure 4 shows the distributions of various parameters, including the original total mass, formation redshift, merger redshift, and final radius (four columns, from left to right) for these four classes of objects (four rows, from top to bottom). Various interesting trends appear in these distributions; in particular, the progenitors of tidal streams (second row) lie at somewhat smaller radii (~ 30 kpc), are slightly older, and have larger original masses than the surviving satellites (top row).

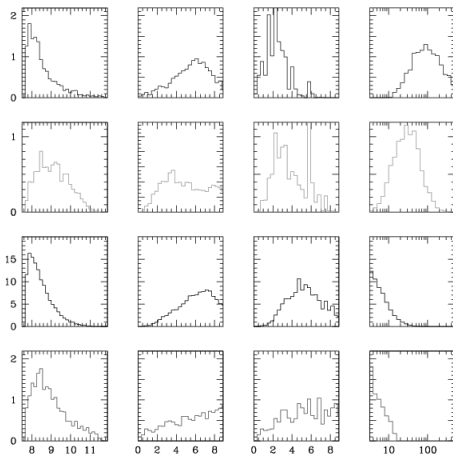


Figure 4. Distribution of original total mass, formation redshift, merger redshift, and final radial position (columns from left to right) of stellar systems that survive at the present-day, tidal stream progenitors, disrupted systems and central mergers (four rows, from top to bottom) in a large set of semi-analytic haloes.

We can compare these predictions with the observations discussed above. On the one hand, only a few streams have been detected in the Milky Way (Sagittarius, Canis, and possibly a few older streams associated with objects such as the massive globular cluster ω Cen; cf. Bekki & Freeman 2003). On the other hand, given the difficulty of detecting older streams, substantial incompleteness is not implausible. Our results suggest that Gaia may expect to sample stars from a much larger population of disrupted systems – on the order of 100. Most of these systems will have merged with the halo at redshifts of 2 or higher, however, and will consist of old stars, strongly mixed in phase-space by repeated scattering from their initial orbits. It will take much more detailed modelling of the disruption and mixing process (cf. Johnston 1998; Helmi & White 1999) to determine how many distinct structures should be detectable in practice.

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