Chapter 1

Introduction

The Galactic satellites form a nearby set of systems which have evolved under the dynamical influence of a large host galaxy. This in itself is not unusual; large-scale surveys have revealed that galaxies are arranged in clusters, where many of the massive galaxies dominate the dynamics of the surrounding smaller systems. However, it is the proximity of the Galactic satellites which make them important to the observer. They are near enough to be resolved into individual stars, allowing accurate measurements of their stellar populations, kinematics, and dynamical evolution. That is, these systems provide a useful tool in the study of ‘near-field cosmology’.

As a satellite system (such as a dwarf galaxy or globular cluster) orbits a large host galaxy, it experiences tidal forces due to the gravitational influence of the host. The potential field injects energy into the satellite, which alters the internal stellar orbits, thereby changing its overall structure. Thus, the dynamical evolution of a small galaxy is heavily dependent on its larger neighbours. During the first few orbits, the tidal field applies a limiting radius to the small system, beyond which stars are no longer bound to the satellite. However, as the disruption continues, some of the outer stars may escape and form tidal tails. The orbit is then altered through dynamical friction, and the satellite spirals towards its host causing an increased level of distortion. Finally, the small galaxy is thoroughly disrupted, and its stars merge into the host system.

This process has been instrumental in the formation of the large-scale structures presently observed. It was the merging of small systems in the early universe which created large objects such as the Galaxy. Thus, the nearby satellite systems will eventually merge with the Galaxy, and are therefore part of an on-going process of galactic accretion. By studying the structure and kinematics of these systems, it may be possible to detect signs of tidal distortion. This is most apparent in the Sagittarius dwarf galaxy (Ibata et al. 1994), whose structure has been heavily disrupted by the potential field of the Galaxy. Such events are important towards our understanding of galactic dynamics. The level of distortion is sensitive not
only to the mass of the Galaxy, but also to the distribution of this mass (Sackett et al. 1994; Johnston et al. 1999b; Ibata et al. 2001). Also, these objects appear dominated by dark matter. Therefore, this distortion can be used to determine the amount of DM a satellite contains, and also to find how efficiently a dark halo will conserve the luminous mass within a bound system while it is being perturbed. That is, the satellite systems are an useful tool to determine the role of dark matter in galactic dynamics.

1.1 Dwarf Galaxies

The past two decades have witnessed a revolution in the study of faint galaxies. With the advent of larger telescopes, more efficient detectors and new observing techniques, we are now able to reach stars down to fainter limiting magnitudes over large areas of the sky. In recent years, the complex nature of dwarf galaxies has consequently become apparent. Historically, dwarf spheroidal (dSph) galaxies were seen essentially as large, diffuse globular clusters, uncomplicated structures consisting of a single-age stellar population. This view has been changed on several fronts. In terms of star formation, Mould & Aaronson (1983) first showed that the stellar population of the Carina dSph is complex. Subsequently, the star formation histories of nearby dwarf spheroidal galaxies have been revealed to be complex and varying from system to system. For example, whereas the Ursa Minor dSph consists mainly of old stars (Olszewski & Aaronson 1985; Mighell & Burke 1999; Carrera et al. 2002), 80% of the stars in Leo I formed in the last seven billion years (Gallart et al. 1999).

The importance of dwarf galaxies in the dark matter regime has also become apparent. Measurements of individual stellar velocities in the dSph systems reveal that they are surprisingly massive for their luminosity. The optical mass-to-light ratios of some dwarf galaxies are found to be \( \sim 100 \) or more, indicating that these objects are dominated by dark matter. Indeed, dwarf galaxies are the darkest objects in the universe which we can directly observe. The velocity profiles of these objects are flat (for example, Mateo 1997, 1998; Kleyna et al. 2001), revealing that the dark halos of dwarf galaxies extend beyond the detected limits of the luminous material. That is, the luminous material of dwarf galaxies is only a minor component of such objects.

In the standard Cold Dark Matter (CDM) scenario, fluctuations in the power spectrum during the early times of the Universe resulted in small clumps of dark matter with masses \( \sim 10^6 M_\odot \) (for example, Susa & Umemura 2004 and references therein). By redshift \( z \sim 10 \), dwarf galaxies have formed through the merger of these small dark halos. Indeed, Ricotti & Wilkinson (2004) predict that despite existing for several crossing times, the inner region of isolated dark halos should
exhibit little structural evolution after $z = 10$. The majority of these dwarf galaxies were not sufficiently isolated to survive to the present day, and have since merged to form the large scale structure now visible. Thus, there are two important points about the current crop of Galactic dSphs: (i) they are survivors from a previous epoch, and; (ii) they formed from accretion of smaller systems in the early universe.

Thus, the structure of a dwarf galaxy reflects its dynamical evolution. If dwarf galaxies are built up through the accretion of smaller dark halos, then it may be possible to find the primordial building blocks in the local universe (Freeman & Bland-Hawthorn 2002). As an example, the Ursa Minor (UMi) dSph contains a kinematically cold association of stars towards its centre, which may represent a primordial clump of dark matter Kleyna et al. (2003). Chapter 2 contains evidence of substructure in the Fornax dSph, possibly the remnant of a merger between this system and a gas-rich companion $\sim \! 2$ Gyr ago. This represents the first event of this type detected in a dwarf galaxy.

Generally, the dynamical evolution of the satellite dSph galaxies has been most strongly influence by the tidal field of the Galaxy. Martínez-Delgado et al. (2001) and Palma et al. (2003) found a significant population of UMi stars beyond the nominal tidal radius, and stated this represents tidal interaction with the Galaxy. The earlier survey by Irwin & Hatzidimitriou (1995) of the dSph galaxies found evidence of extra-tidal material in many of these objects. However, a measurement of the mass-to-light ratio assumes the system is in virial equilibrium. Thus, tidal disruption by the Milky Way may result in an artificially inflated estimate of the virial mass (Kuhn & Miller 1989). Chapter 3 examines the structure of the Sculptor dSph using a combined photometric/spectroscopic wide-field survey, with the aim of detecting extra-tidal material. This allowed an estimate of the level of interaction between the Sculptor system and the Galaxy.

### 1.2 Globular Clusters

The dynamical evolution of the globular clusters is similar to that of the dwarf galaxies, however there are important differences. Globular clusters are significantly smaller, and, given that both types of object have roughly equivalent velocity dispersions, they also demonstrate a smaller crossing time. Also, the volume density of stars in a cluster is substantially larger than in a dwarf galaxy. The result is that the rate of stellar encounters in a globular cluster is extremely large compared to a dSph galaxy, and its dynamical evolution will therefore proceed at an increased rate. These encounters cause stars to exchange kinetic energy, which will drive a cluster towards a Maxwellian velocity distribution, when it will have achieved a state of relaxation. The relaxation time for a typical Galactic globu-
lar cluster (GGC) is of the order of $10^9$ yr (Binney & Tremaine 1987; Gnedin & Ostriker 1997), significantly less than the age of all GGCs.

The process of two-body relaxation also results in equipartition of energy, thus the massive stars sink towards the centre of the cluster, and the lighter stars diffuse outwards. If a star gains enough energy, it will pass beyond the limit of the cluster. Thus, globular clusters are constantly losing mass through diffusion. However, the presence of a massive host accelerates this destruction. Over the period of a few orbits, the tidal field of the Galaxy has imposed an outer limit on each of its clusters, labelled the ‘tidal radius’. As it continues to orbit the host, energy is inserted into the cluster, heating the internal stellar orbits. Similar to a dwarf galaxy, this process will increase the rate of stellar mass loss.

Due to their proximity, globular clusters experience gravitational shocks when passing near the bulge or through the disk component of the Galaxy. Simulations have shown that the bulge greatly increases the rate of destruction for clusters on a highly elongated orbit (for example, Oh & Lin 1992; Gnedin & Ostriker 1997; Johnston et al. 1999a; Combes et al. 1999). The cluster is elongated such that its long axis points towards the centre of the Galaxy. However, the dominant cause of globular cluster destruction arrives in the form of gravitational shocks from the Galactic disk. Disk shocking is a result of the system crossing the thin disk, which displays a location-dependent gravitational potential. Initially, the cluster is vertically compressed. This effect soon reverses as the cluster is elongated along the vertical axis, and stars are lost in the form of tidal tails. Numerical modeling indicates that a cluster rotating in a prograde direction will experience an increased rate of mass loss (Combes et al. 1999).

Consequently, wide-field studies have attempted to detect tail-like structures around nearby globular clusters to determine the dynamical evolution of these systems, and thereby measure the tidal field of the Galaxy. Grillmair et al. (1995) analysed photographic photometry for twelve Galactic globular clusters, selecting candidate cluster stars based on colour and magnitude. This method reduced contamination from the Galactic stellar population, and they found evidence for tidal extensions in several clusters. Similarly, Leon et al. (2000) obtained two-colour photographic data for 20 GGCs, and conducted a search for tidal tails similar to the Grillmair et al. process. Leon et al. found strong evidence for tidal tails in the majority of these systems.

However, the most successful result to date has been that of Odenkirchen et al. (2001, 2003), who detected substantial tidal tails extending from the globular cluster Palomar 5. These structures cover $10^\circ$ on the sky (Fig. 1.1), which corresponds to 4 kpc at the distance of the cluster. Odenkirchen et al. (2003) estimate the total mass of these structures to be 1.2 times the mass of the cluster. This object has experienced multiple disk crossings, which have caused the majority of
its stars to escape. Indeed, Odenkirchen et al. estimate that the original cluster mass may have been 10 times the present value. Given that the tails are so extensive, they provide a useful tool to study to gravitational potential of the Galaxy.

The possibility of tidal tails extending from the globular cluster ω Centauri remains disputed. Based on photographic plates, Leon et al. (2000) detected tails around this system, and estimated their total mass to be approximately 1% of the cluster mass. However, given the low Galactic latitude of ω Cen ($b = 15^\circ$; Harris 1996), the differential extinction across its surface is substantial, and therefore the extra-tidal structures may be artefacts of dust absorption. Law et al. (2003) adjusted the 2MASS photometry in the vicinity of the cluster using the dust maps of Schlegel et al. (1998), and found that this process removed the tidal tails. Consequently, Chapter 4 contains the results of a wide-field survey of ω Cen. A wide-field, CCD-based photometric survey of the cluster was used to remove the majority of contaminating field stars. This was followed by a spectroscopic survey, which further refined the number of candidate extra-tidal stars. These results gave an upper limit to the amount of mass beyond the cluster tidal radius.