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Tidal Tails and the Shape of the Dark Matter Halo

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Abstract: Cold dark matter cosmologies successfully accounts for the distribution of matter on large scales. On smaller scales, these cosmological models predict that galaxies like our own Milky Way should be enveloped in massive dark matter halos. Furthermore, these halos should be significantly flattened or even triaxial. Recent observational evidence, drawn from the demise of the Sagittarius dwarf galaxy as it is cannibalized by our own, indicates that the potential of the Milky Way must be close to spherical. While the precise interpretation of the observational evidence is under debate, an apparently spherical halo may signify a pronounced failing of dark matter models, and may even indicate a failure in our fundamental understanding of gravity.

Keywords: cosmology: theory, dark matter — galaxies: halos — Galaxy: formation, halo

1 Introduction

Within the current cosmological paradigm (e.g. Spergel et al. 2003), the formation and evolution of structure in the universe is driven by the motions of cold dark matter. Here massive galaxies like the Milky Way grow over time via the accretion of smaller systems, a process which should be still underway today. Furthermore, our Milky Way should be enveloped within a massive halo of dark matter which represents the dominant mass of the Galaxy. Given the nature of cold dark matter, such a halo should be significantly flattened, or even triaxial, with a typical axis ratio of $q = 0.5 \pm 0.15$ (Dubinski & Carlberg 1991; Dubinski 1994; Jing & Suto 2002). It should be noted, however, these predictions come from purely dark matter simulations, and it has been found that the addition of a baryons can significantly influence the evolution of the form of the dark matter halo, resulting in mass distributions which, while still flattened, are more spherical (Kazantzidis et al. 2004). Interestingly, other proposed candidates for dark matter, such as cold-molecular gas, then the flattening of dark matter halos will be more pronounced, with an axis ratio of $q \sim 0.2$ (Pfenniger & Combes 1994; Pfenniger, Combes, & Martinet 1994).

While the existence of dark matter is acknowledged by the majority of the astronomical community, its acceptance is not universal. Some have suggested that a lack of understanding of the influence of gravity at large distances may imitate the existence of dark matter; astrophysically, the most developed of these ideas is that of Modified Newtonian Dynamics (MOND; Milgrom 1983). Within this framework, gravitational forces would arise solely from the material within the luminous disk of the Milky Way, resulting in the gravitational potential appearing essentially spherical at large distances (Milgrom 2001).

Determining the shape of dark matter halos, therefore, is fundamentally a test of the nature (if not the existence) of dark matter. Measuring the shapes of dark matter halos is amenable through a number of approaches, such as through the kinematics of polar ring galaxies (Sackett et al. 1994) and the weak shearing of gravitationally lensed galaxies (Hoekstra, Yee, & Gladders 2004); while these possess a broad agreement with the predictions of cold dark matter expectations, interpretations can be complicated by a number of physical effects. Our location within the Milky Way limits the available tests of the shape of our own dark matter halo, although Olling & Merrifield (2000) have employed the flaring of the gas disk and stellar kinematics to rule out a significantly flattened halo. One of the simplest approaches to determine the shape of a dark matter halo would be to consider the evolution of small, tracer masses as they orbit a galaxy. To date, however, the limited spatial and kinematic information available on individual members of the halo population have prevented this approach from coming to fruition.

2 Tidal Tails & Halo Streams

Cold dark matter scenarios predict that large galaxies like the Milky Way grow by means of the cannibalization of smaller systems (e.g. Kauffmann, White, & Guiderdoni 1993). The overall accretion, however, is a slow process, with repeated encounters tearing off stars until the dwarf companion is completely destroyed. The tidal debris steadily spreads out over the orbit of the dwarf, growing

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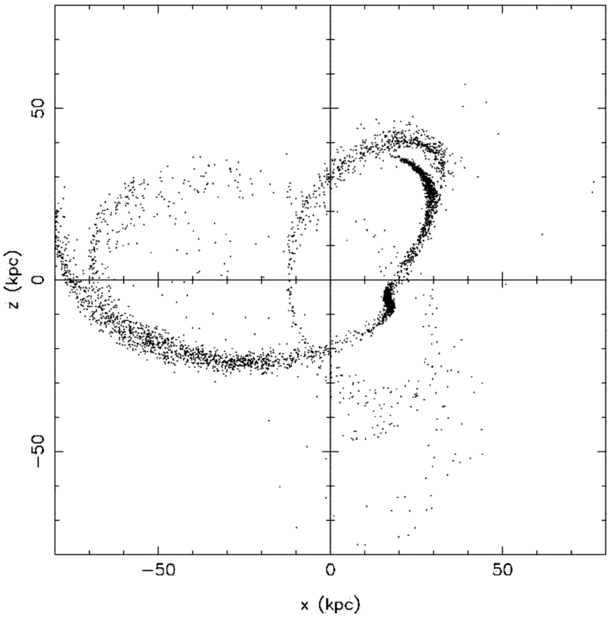

Figure 1 A typical outcome for a numerical simulation of the demise of the Sagittarius Dwarf Galaxy with the potential of the Milky Way (Ibata et al. 2001b). The body currently identified as the dwarf galaxy can be seen as a small knot at (20, −5) in the extensive stream of tidal debris that has been torn from the galaxy.

into an extensive tidal stream of stellar material that can completely wrap the consuming galaxy (see Figure 1).

The coherent nature of such tidal tails, however, suggests that they would provide a superb probe of the form of the dark matter halo, as each point along the stellar stream presents a snapshot of the spatial and kinematic properties (Johnston 1998). Furthermore, given the predictions of cold dark matter cosmologies, the halo of the Milky Way should be awash with the dismembered corpses of many hundreds or thousands of cannibalized dwarf galaxies. However, observations of the local environment of the Milky Way does not support this position, with the Galaxy accompanied by only a handful of dwarf companions, far less that cold dark matter predictions; this missing satellite problem has become the focus of significant debate (e.g. Klypin et al. 1999). Furthermore, most of the dwarfs appear to be relatively unperturbed by their interaction with the Galaxy, lacking the tidal tails necessary for studying the halo.

3 The Sagittarius Dwarf

In 1993 the first candidate for an ongoing example of a cannibalized system was made with the serendipitous discovery of the Sagittarius Dwarf Galaxy (Ibata, Gilmore, & Irwin 1994). Located at a distance of only 25 kpc, it evaded detection by being located beyond the Galactic bugle. Additionally, it proximity ensures its projected stellar surface density is extremely low, easily losing itself in the general Galactic populations. Currently heading into the disk of the Milky Way, the orbit of the Sagittarius Dwarf Galaxy brings it perilously close to the Milky Way, where the Galactic tidal forces steadily strip material from the dwarf. Ranging between 16 kpc and 60 kpc, the Sagittarius Dwarf Galaxy represents an ideal candidate for a cannibalized companion.

In the years following its discovery, stellar material was found further and further from the core of the dwarf galaxy, and a tail of tidally shed debris was established by stealth. However, to fully characterize the stellar stream, a more global view of the halo was required. This was provided by a study of carbon stars scattered throughout the Galactic halo (Totten & Irwin 1998; Totten, Irwin, & Whitelock 2000); these evolved stars are intrinsically luminous and so provide a potent probe of the mass distribution in the halo to large distances.

4 The Shape of the Halo

Ibata et al. (2001b) undertook a study of the distribution of carbon stars identified in the study of Totten & Irwin (1998), treating the carbon stars as tracers of the more extensive stellar stream. For their approach, they assumed a static model for the potential of the Milky Way, drawn from the study of Dehnen & Binney (1998), and examined the demise of Sagittarius dwarf like galaxies as they were cannibalized by the Milky Way. Importantly, for each simulation, the flattening of the Galactic halo was modified from spherical to being quite oblate. This had a striking influence on the structure of the tidal tails; for a spherical halo, the tidal debris streams were confined to a single plane, resulting in a coherent band stars across the sky. The orbit of Sagittarius is within ∼5° of being polar, and this slight tilt has important ramifications for orbits in flattened halos, as the orbit begins to precess, with the rate of precession increasing as the halo becomes flatter.

Figure 2 graphically illustrates this. The lower left-hand panel presents the sky distribution of stars in the halo carbon star survey. The solid line in this panel denotes the path of the Sagittarius dwarf galaxy across the sky. The three remaining panels presents the distribution of stellar debris for various halo flattenings, from spherical ($q = 1$) to quite flattened ($q = 0.5$). For the spherical case, a neat, collimated stream of stars crosses the sky. For flattened halos, however, the induced precession has destroyed this structure which, by the $q = 0.5$ case, appears as an almost random scattering of stars throughout the Galactic halo.

In comparing the results of these numerical simulations to the form of the Sagittarius dwarf tidal stream drawn from the halo carbon star survey, Ibata et al. (2001b) concluded that the best match between the data and theory occurred if the dark matter in the Galactic halo is distributed almost spherically, with oblate form for the halo ($q < 0.7$) being strongly ruled out. Given the expectation for flattened dark matter halo, this suggestion that the Milky Way possesses a spherical halo is rather surprising.

5 Recent Results

While the study of Ibata et al. (2001b) used only a small number (∼50) carbon stars within the Galactic halo, the spectacular all-sky picture obtained as part of the 2MASS

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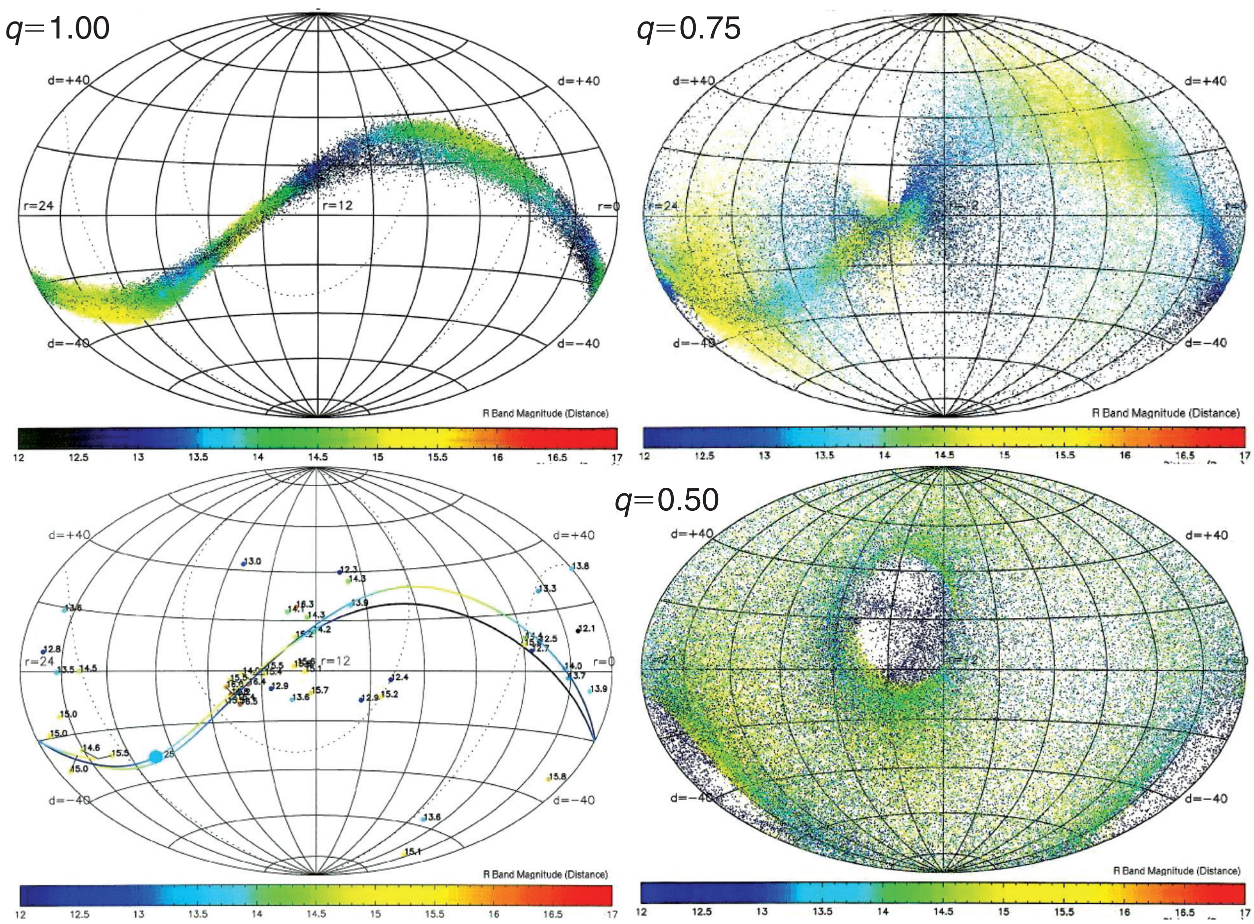

Figure 2 The lower left-hand panel presents the distribution of carbon stars in the Galactic halo (Totten & Irwin 1998; Totten, Irwin, & Whitelock 2000); the solid line accompanying these represents the projection of the orbit of the Sagittarius Dwarf Galaxy with colour-coding for distance. The remaining panels present the results of a series of simulations for the demise of the Sagittarius Dwarf Galaxy within Milky Way dark matter halos with differing flattenings. Clearly, as the flattening increases (i.e. q gets smaller than unity) the tidal debris in the stream strongly precesses, destroying any coherent structures in the halo.

survey (Majewski et al. 2003) yielded many thousands of M-giants within the tidal stream of Sagittarius. As with the carbon star survey, the stream appears to be well collimated and crosses the entire sky, prompting the discoverers to further claim that the dark matter halo must be close to spherical.

Revised numerical modelling of the Sagittarius dwarf tidal stream has somewhat clouded the issue. Helmi (2004a) has argued that the tidal streams detected in 2MASS are dynamically young, with the material torn off in the last ~1–3 Gyr, and so while dynamically old stars may show signs of significant precession due to halo flattening, the dynamically youthful stars can appear quite coherent, almost irrespective of the true oblateness of the dark matter. Furthermore, Helmi (2004a) suggests that the models presented by Ibata et al. (2001b) are flawed, allowing the body of Sagittarius to become completely disrupted too early, with all streams being dynamically old. Intriguingly, in a subsequent publication (Helmi 2004b) analyzed the kinematic properties of the dynamically older tidal streams identified in 2MASS, concluding that the dark matter halo of the Milky Way must be in fact prolate, with a preferred axis ratio $q \sim 1.7$.

More recently, Law et al. (2004) undertook a detailed analysis of the 2MASS view of the Sagittarius dwarf galaxy, focussing not on the thickening of the tidal streams due to the action of precession, but rather the three-dimensional structure of the streams and their projected configurations upon the sky. As with Ibata et al. (2001b), overly oblate and prolate halos are ruled out, with the preferred shape again being close to spherical. This, however, should be contrasted with the results of Martínez-Delgado et al. (2004) who considered wrapped portions of the tidal debris stream at distances of more than 45 kpc, finding the best-fit orbit to be consistent with a halo flattening of $q = 0.5$. Therefore, in summary, the question of the shape of the dark matter halo is still a matter of considerable debate, observations, and modelling.

6 The Future

While Sagittarius remains the most extensive tidal stream within the Galactic halo, large-scale surveys are begin to reveal the presence of systems undergoing significant tidal disruption, including the spectacular tidal tails of the globular cluster, Pal5 (Odenkirchen et al. 2003; Dehnen et al.

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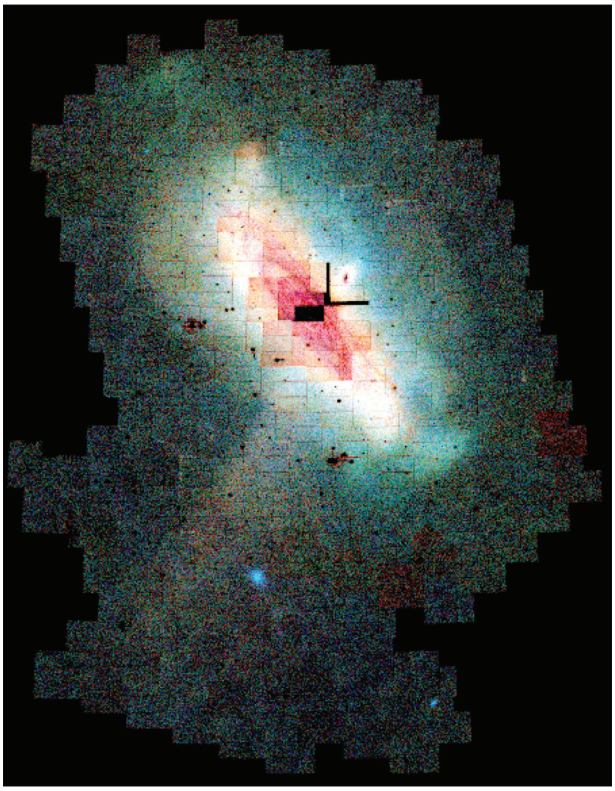

Figure 3 The results of the INT/WFC survey of the halo of the Andromeda Galaxy. The picture covers an area of ~40 square degrees and the typically visible portion of the galaxy, encompassing the disk and bulge, is contained within the central few degrees. The pronounced stellar stream is clearly visible extending below the disk and additional clumps and wisps of substructure are visible (image courtesy of Mike Irwin & Alan McConnachie).

2004), and the Monoceros stream/Canis Major system which is wrapped around the equator of the Milky Way (see Conn et al. 2005, and references therein). The spatial and dynamical properties of such systems will depend implicitly on the mass distribution of the Galaxy, and hence future modelling will provide further constraints on the shape of the dark matter halo.

Clearly a single measurement of the shape of a dark matter halo of the Milky Way does not rule out the cold dark matter hypothesis; the Milky Way could simply represent an outlying example on the overall distribution of halo shapes (Dubinski 1994), and hence further measurements of the shape of other galaxy halos are required. Unfortunately, resolving individual stars in stellar streams is possible only in the nearest galaxies to the Milky Way.

Recently, technological advances and the advent of wide-field CCD cameras have allowed our nearest large companion, the Andromeda Galaxy, to be mapped to significant depths ($g \sim 23.5$, selecting individual stars on the red giant branch) over an appreciable area (~40 square degrees), covering the halo out to more than 60 kpc. A simple by-eye examination of the stellar distribution reveals a most striking feature, an extensive stream of stars extending well beyond the disk of Andromeda (see Figure 3). Further examination of survey reveals that the halo of M31 is basically a messy places, with strong spatial (and metallicity) variations (Ferguson et al. 2002), possibly pointing towards a more violent interaction history.

The advent of 10-m class telescopes has provided the opportunity to obtain the spectra of individual stars within the stellar stream, allowing the determination of velocities of an accuracy of better than 10 km s^{-1} (e.g. Ibata et al. 2004). To this end, a dedicated spectroscopic survey of the substructure in M31 with DEIMOS on the Keck telescope has been underway for a couple of years. Utilizing multi-slit masks, and for some fields taking advantage of a custom built narrow-band filter to increase target density, this survey has now obtained radial velocities for 768 stars, including three fields along the tidal stream.

Coupled with the knowledge of the three-dimensional structure of the streams (determined via the tip of the red giant branch by McConnachie et al. 2003), Ibata et al. (2004) sought to determine the orbital properties of the Andromeda stream, and hence measure the shape of the dark matter halo in M31. Unfortunately, the currently scant kinematic information limits the analysis, with the study providing limits on the total mass within the Andromeda galaxy. To this end, a larger kinematic survey of the halo of M31 is currently underway, providing detailed kinematics along and yielding a determination of the shape of its dark matter halo. If this too appears to be spherical, then we may have to question our current cold dark matter paradigm, if not the nature of gravity itself.

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