Dynamics of the Galaxy’s Satellites

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Abstract. The Milky Way’s satellites provide unique information about the density of the Galactic halo at large radii. The inclusion of even a few rather inaccurate proper motions resolves an ambiguity in older mass estimates in favour of higher values. Many of the satellites are concentrated into streams. The dynamics of the Magellanic Stream provided an early indication that the halo reaches out to beyond 100 kpc. Tidal forces between the Clouds are currently disturbing the Clouds’ internal dynamics. One would expect this damage to worsen rapidly as the tidal field of the MW excites the eccentricity of the Clouds’ mutual orbit. This process, which has yet to be completely modelled, is important for understanding the degree of self-lensing in searches for gravitational lensing events. The Sagittarius Dwarf galaxy very likely contributes significantly to the Galactic warp. The direction of the warp’s line of nodes is incorrectly predicted by the simplest models of the Dwarf’s orbit. More sophisticated models, in which a complex distribution of stripped dark matter is predicted, may be more successful.

1. Introduction

The flat rotation curves of many external galaxies have convinced us that the space around galaxies is filled with dark matter of some sort. Elucidating the nature of this matter is one of the central problems of contemporary astronomy. By learning more about the dynamics of the ∼ 100 kpc around galaxies, we may determine what this matter is.

Direct measurement of the Milky Way’s circular-speed curve becomes problematic beyond $R_0$ (e.g., Binney & Dehnen, 1997). We can, however, probe the dynamics of the outer Milky Way with observations of objects that are too faint to be studied in much detail around external galaxies, so in some respects we know more about the Galactic dark halo than about the dark halo of any other galaxy.

2. Equilibrium Spherical Models

In the simplest picture, the dark halo is spherical and phase mixed. Over the last decade and a half many attempts have been made to constrain the mass of such a halo from observations of the line-of-sight velocities of distant globular clusters and dwarf satellite galaxies (Little & Tremaine 1987; Zaritsky et al.
The masses inferred in these studies depend strongly on whether or not the most distant satellite, Leo I, is assumed to be bound to the Milky Way. Wilkinson & Evans (1999) have revisited this problem and shown that when radial velocities are complemented by proper motions, consistent mass estimates are obtained with or without Leo I. Figure 1 illustrates this result. In the top panels the likelihood peaks at models that differ in mass by a factor of 2 depending on whether Leo is included (full contours) or not. This is the case in which only line-of-sight velocities are employed. In the lower panels, which include five proper motions, the likelihood peaks at masses that differ insignificantly whether Leo I is included or not. Quantitatively, the mass required inside 50 kpc is \( M_{50} = (5.45 \pm 0.15) \times 10^{11} M_\odot \), while that required inside 100 kpc is \( M_{100} = (10 \pm 0.4) \times 10^{11} M_\odot \). Large though they are, these masses are still less than half the mass of the Local Group, \( M_{LG} = (6 \pm 2) \times 10^{12} M_\odot \) (Schmoldt & Saha 1998), so most of the mass of the Universe lies outside the halos of galaxies, just as several cosmological arguments predict.

It is to be expected that proper motions provide considerable leverage on the problem because the Sun lies close to the centre of the halo, with the consequence that the tangential motions of distant objects are virtually unconstrained by line-of-sight velocities. The upper panels in Figure 1 show that in the absence of proper motions, highly radially anisotropic models are strongly favoured, and with Leo I excluded these models have rather low masses. When proper motions are included, these anisotropic models become less likely, and larger masses are required. What is perhaps remarkable is that such dramatic shifts in likelihood are obtained with the extant proper motions, in which the errors are large – of order 0.3 mas yr\(^{-1}\) in proper motions that lie in the range 2.7 to 0.3 mas yr\(^{-1}\). Over the coming decade, as results from the upcoming generation of astrometric satellites (DIVA, FAME, SIM and GAIA) become available, the errors in these proper motions will be dramatically reduced, and many additional proper motions will become available. The data will then determine the mass profile of the Galactic halo to high precision.

3. Streams and Infall

At 100 kpc from the Galactic centre, the dynamical time is \( t_{\text{dyn}} = \frac{1}{\pi} \sqrt{R^3/GM} \sim 0.8 \text{Gyr} \), so we cannot expect the outer halo to be dynamically relaxed. In particular, at large radii we should expect material to be falling in to the Milky Way for the first time (Gunn & Gott, 1972). Recently, Blitz et al. (1999) and Braun & Burton (1999, 2000) have powerfully restated the case that compact high-velocity clouds are such infalling material. Indirect evidence for past infall comes from the spread (\( \sim 7 \text{Gyr} \)) in the ages of globular clusters (Stetson, van den Bergh & Bolte, 1996), the classic G-dwarf problem (van den Bergh, 1962; Binney & Merrifield 1998, §10.7.2), the counter-rotation of the system that is formed by globular clusters with metallicities \(-1.7 < [\text{Fe/H}] < -1.3\) (Rodgers & Paltoglou 1984), and the existence of satellite streams.

Lynden-Bell (1976) pointed out that the Galaxy’s satellites appear to lie along a few great circles in the sky. Lynden-Bell & Lynden-Bell (1995) markedly
Figure 1. Contours of equal likelihood for mass models of the Galactic halo, with (full) and without (dotted) data for Leo I. When five proper motions are used, one obtains the lower panels, while the upper panels are obtained when only line-of-sight velocities are used. The left and right panels derive from models with different assumptions about the halo’s radial density profile. The parameter $\beta$ controls the anisotropy of the model’s velocity distribution, being positive for radial anisotropy. [From Wilkinson & Evans (1999).]
refined this conjecture by adding kinematic data to the analysis. They identified four high-quality streams with the following members:

- Fornax, Pal 14, Pal 15, (Eridanus ?)
- Magellanic Clouds, Draco, Ursa Minor, (Sculptor, Carina ?)
- NGC 2419, NGC 7006, Rup 106, (Ter 7, Sagittarius Dwarf ?)
- Pal 2, Arp 2, Sagittarius Dwarf, (Ter 7 ?)

Interest in these streams is currently very high as it has been suggested (Johnston et al., 1999) that the Galactic potential could be accurately determined if the space velocities of a few objects in each stream could be reliably measured. SIM and GAIA will make the measurements, but I am optimistic that the potential will have been precisely mapped before SIM or GAIA data become available through detailed modelling of observations of more numerous classes of halo tracers, such as blue horizontal-branch stars, for which less complete data are available for any individual object (e.g., Dehnen & Binney, 1996).

3.1. The Magellanic Stream

Far and away the best studied stream is that of the Magellanic Clouds, which includes a stream of HI that reaches nearly half way across the southern sky. Murai & Fujimoto (1980) first gave the currently accepted model of the Magellanic Stream. From the fact that the LMC and SMC form a binary system, they deduced that the Clouds are near pericentre rather than near apocentre, as had been previously thought. It followed that the gaseous stream was trailing the Clouds, and an extensive Galactic halo was required to generate the observed line-of-sight velocities along the stream. Any doubt as to the essential correctness of the Murai & Fujimoto model has been eliminated by the measurement of the LMC's proper motion (Jones, Klemola & Lin 1994; Kroupa & Bastian 1997), which the model correctly predicted.

Most modelling of the Magellanic Stream has used test particles, with the effect of dynamical friction against the Galactic halo (which is dynamically important) added analytically. Gardiner & Noguchi (1996) have usefully extended this kind of analysis by representing the SMC by a self-consistent $N$-body model. Their simulations give a convincing picture of the formation of the Magellanic bridge and stream from material that has been tidally torn from the disk of the SMC. This kind of modelling is important because we need more convincing estimates of the amount of gravitational self-lensing to be expected within the Clouds (Sahu, 1994; Kerins & Evans, 2000), and this depends strongly on the vertical structure of the Clouds, which is in turn going to depend on the tidal distortion of one Cloud by the other. The model of Gardiner & Noguchi (1996) does not predict as much self-lensing (Graff & Gardiner 1999) as now seems probable (Kerins & Evans, 2000), but the parameter space to be explored, which includes the orientation of the disk of each cloud and the mutual orbit of the Clouds relative to the orbit of the Clouds' barycentre around the Milky Way, is large and has yet to be fully explored.
3.2. Dynamics of the Sagittarius Dwarf

Since its discovery 16 kpc behind the Galactic centre (Ibata et al. 1994), the Sagittarius dwarf galaxy has attracted a good deal of attention. Like the Clouds, the Dwarf is on a nearly polar orbit, but the plane of its orbit is nearly orthogonal to that of the Clouds’ orbit. The period of the Dwarf’s orbit is remarkably short, \( \lesssim 1 \) Gyr, and there is general agreement that it is currently being torn apart by the Galaxy’s tidal force. How long has the Dwarf been on this exposed orbit?

Several studies have concluded that the Dwarf could not survive for a Hubble time on its current orbit. The exceptions to this rule are Ibata & Lewis (1998) and Helmi & White (2000). Ibata & Lewis showed that a very nearly homogeneous dark-matter halo for the Dwarf of mass \( 1.2 \times 10^9 \, M_\odot \) can survive for a Hubble time, although it has by then been tidally stripped of \( \sim 60\% \) of its mass. Helmi & White show that models with initial mass \( 0.57 \times 10^9 \, M_\odot \) and \( 1.2 \times 10^9 \, M_\odot \) yield reasonable matches to the observations after a Hubble time, although they have by then been stripped of almost 90% of their mass. Whether the stripped mass is associated with light and is optically traceable depends on the assumed radial variation of the mass-to-light ratio within the initial model.

Could the Dwarf have formed on its present orbit, along which tidal shredding is such an efficient process? Or has the Dwarf migrated to its current short-period orbit from a longer-period and safer one? Zhao (1998) made the ingenious proposal that the Dwarf was deflected onto its current orbit by the Magellanic Clouds as the systems passed one another near a Galactic pole. The problem with this idea is to understand how the Dwarf could have been deflected by a large angle on encountering an object with a similarly soft potential at a speed of \( \sim 300 \, \text{km} \, \text{s}^{-1} \).

Another mechanism by which the Dwarf could have moved to a short-period orbit is dynamical friction. Its current mass is so small that it will now be suffering negligible frictional drag. But we have seen that it must currently be losing mass rapidly, and will have been more massive in the past. Jiang & Binney (2000) show that there is a one-parameter family of initial configurations of the Dwarf that evolve into something like its present configuration over a Hubble time. At one extreme we have a Dwarf of mass \( \sim 10^{11} \, M_\odot \) starting from Galactocentric radius \( \sim 250 \, \text{kpc} \). At the other extreme the initial mass is \( \sim 1.2 \times 10^9 \, M_\odot \) and the Dwarf starts from \( \sim 60 \, \text{kpc} \), very much as in the models of Ibata & Lewis and Helmi & White.

4. Warp of the Milky Way

On any model in which the Dwarf has an effectively polar orbit, virtually all the Dwarf’s initial mass is now in a polar annulus. The mass of this annulus can be as little as \( 10^9 \, M_\odot \) or as much as \( \sim 10^{11} \, M_\odot \), and its angular momentum is uncertain by even more than two orders of magnitude, because the higher-mass rings will have larger mean radii. An angular-momentum detector would seem to be the best way of distinguishing between these possibilities. The Galactic disk is just such a detector in that it becomes warped in response to the addition of off-axis angular momentum (Jiang & Binney, 1999). The way the ring of matter stripped from the Dwarf affects the Galactic disc depends sensitively on how nearly polar the Dwarf’s orbit is: if it were exactly polar, there would be no
torque acting between the ring and the Galaxy, and no distortion of the disk. The inclination of the Dwarf’s orbit is not accurately known, but the pole of its orbit is thought to lie near \((l, b) = (85^\circ, 25^\circ)\). With this orientation the ring is pulling the northern disk down and the southern disk up, and the vector of the torque on the disk points from the Galactic centre towards the Sun. Because it rotates clockwise, the disk’s angular-momentum vector points to the SGP, and the Dwarf should be rotating it up towards the Sun. Consequently, the line of nodes should lie in the direction \(l = 90^\circ\), rather than along \(l = 0^\circ\) as observed.

This failure of the model to generate the correct orientation for the warp’s line of nodes is frustrating because the magnitude of the predicted effect is about right. To give a concrete example, consider the effect upon the disc of a ring of mass \(2 \times 10^9 M_\odot\) and radius 25 kpc whose polar axis lies at \((l, b) = (90^\circ, 25^\circ)\). If we adopt the simplest model of the Galactic potential, \(\Phi_{MW} = v_c^2 \ln r\) with \(v_c = 220\) km s\(^{-1}\), we find that the angular momentum vector of a star on a circular orbit of radius 16 kpc shifts towards the current solar position at a rate \(0.43^\circ\) Gyr\(^{-1}\), so after 10 Gyr the star would oscillate \(\sim 1.2\) kpc around its original orbital plane. The HI data require just such excursions (e.g., Fig. 9.24 of Binney & Merrifield, 1998).

Two points should be considered when trying to resolve the problem posed by the observed line of nodes. The first is the Magellanic Clouds: their orbit is almost perpendicular to that of the Dwarf, so do they not generate a warp whose line of nodes agrees nicely with that observed? The answer is ‘no’ for two reasons. First, the orbit of the Clouds is so nearly polar [its pole lies near \((l, b) = (190^\circ, 3^\circ)\)] that a uniform ring with this orientation would apply only a very small torque to the disk. The Clouds are never the less capable of inducing a warp because they have not yet been uniformly smeared around a ring, and the period of their orbit is long enough that, in a useful approximation, they can be considered stationary. At their current location they are pulling the southern disc down and thus applying a torque that acts on the same line as the torque from the Dwarf’s ring, but has opposite sign (Garcia-Ruiz, Kuijken & Dubinski, 2000). Consequently, the associated line of nodes is parallel to that predicted by the Dwarf.

Unless the mass of the Dwarf is at the bottom end of expectations, the Dwarf must contribute non-negligibly to the Galactic warp. The problem with the line of nodes just described may be resolved by precession of the Dwarf’s stripped material. Since it is torquing the disk, this material must itself be precessing, and the current position of the Dwarf’s luminous core may not be a good guide to the current location of the mass of dark matter that was stripped some Gyr ago. At present no model is sufficiently sophisticated to enable one to evaluate this idea quantitatively.

5. Conclusion

The Milky Way’s satellites provide a wealth of information about the extent and history of our very typical \(L^*\) galaxy. Natural extensions of existing models of the dynamics of streams promise a rich harvest of insights into some of the most important questions in astronomy.
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