Part VI

The Milky Way and the Local Group of Galaxies

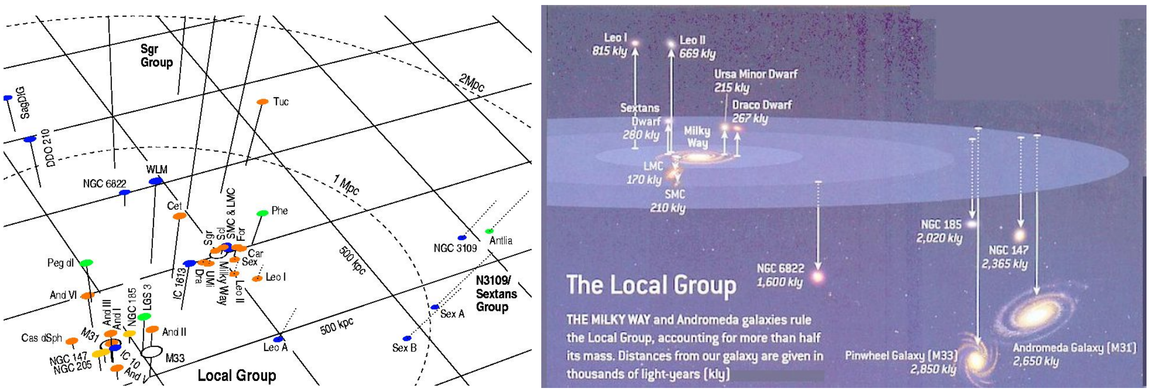

Figure 6.1: Two views of the Local Group of galaxies.

Introduction: The Milky Way: Components

General Characteristics

The Milky Way is a fairly typical, large disk galaxy, classified as SBbc

The luminous parts consists of a disk of Pop. I stars and a bulge of older Pop. II stars.

The Milky Way contains around $2 - 4 \times 10^{11}$ stars.

The Disk

- The Sun is located in the disk, about 8.5 kpc from the Galactic Centre.
- The disk also has clusters of young stars and HII regions, and dust and gas.
- Stellar disk extends out to $\sim$ 15 kpc.
- Stars typically move on circular orbits with a velocity of $\sim$ 200 km s^{-1}, with smaller random components ($\sim$ 30 km s^{-1}).
- The gas is mostly observed as an HI layer which flares at large radii.
- HI observed out to $\sim$ 20 kpc, with $v \sim$ 200 km s^{-1} – enclosed mass $2 \times 10^{11} M_\odot$.
- The *thin disk* contains 95% of the disk stars and has a scale height of $300 - 400$ pc.
- The *thick disk* stars – scale height of $1 - 1.5$ kpc, metal-poor and are believed to be old.
- There are several spiral arms in the disk (Sagittarius-Carina, Perseus arm).
- Sagittarius-Carina arm can be traced for nearly a full turn and has a pitch angle of $\sim 10°$.

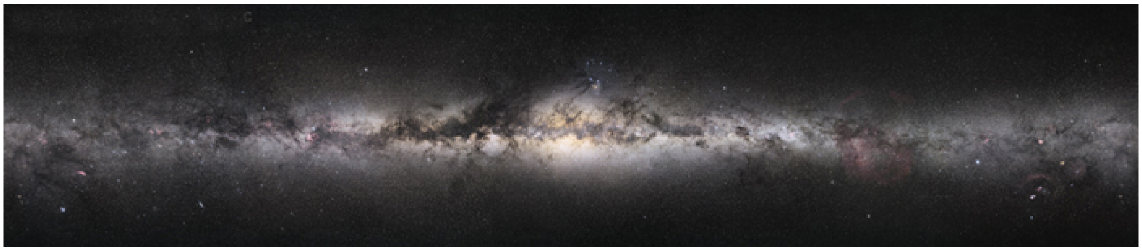

Figure 6.2: Optical panoramic view of the Milky Way.

Central Regions of the Galaxy

- The bulge consists of a population of predominantly low-mass older stars, with higher metallicity than solar.
- The bulge is also rotating.
- The bulge has a bar, though the dimensions of it are unclear.
- Bulge stars tend to have a larger random component to their motion.
- The Galactic Centre contains a black hole, with a mass of $4.3 \times 10^6 M_\odot$ – Sgr A*.
- There are several very young star clusters near Sgr A*, with some very massive stars (Arches and Quintuplet clusters).

The Galactic Halo

- The most massive part of the Milky Way is the very extended halo.
- The halo contains some old metal poor stars (and globular clusters of very old stars).
- These stars have random and often very eccentric orbits.
- Most of the mass of the halo is dark matter of unknown composition.

Companion Galaxies to the Milky Way

There are ~ 10 small companion galaxies to the Milky Way.

The Magellanic Clouds

The best known are the Large and Small Magellanic Clouds, which are 50 kpc (LMC) and 60 kpc (SMC) away. Both are Irregular galaxies and are currently forming stars.

- LMC – $\sim 10\%$ of mass of Milky Way - disk-like morphology.

  Sometimes classified as Magellanic spiral.

  The LMC has a prominent bar.

  Contains the bright star-forming region of 30 Doradus plus other star-clusters.

  LMC does rotate, but orbits are not symmetric about centre of the galaxy.

- SMC – smaller (10× fainter than LMC), seen as end-on view of cigar-like morphology – length perhaps 15 kpc. Stars have no organised motion.

  SMC has bright star-forming regions – brightest is NGC 346.

- Magellanic Stream: series of HI clouds extending for large arc on sky – material believed to have escaped (or been stripped) from LMC and SMC and now trailing the galaxies.

Figure 6.3: Left: The Large Magellanic Cloud (LMC). Right: The Small Magellanic Cloud (SMC).

Other Dwarf Satellite Galaxies

Most other Milky Way companions galaxies are dwarf Spheroidals (dSph).

- These have little or no HI gas and no recent ($< 1-2$ Gyr) star-formation, with some stars > 8 Gyr old (RR Lyraes).

- Examples include the Fornax dwarf, Sculptor dwarf etc.

- Smallest dwarf spheroidals have a luminosity comparable to large globular clusters but are much larger (scale radius of 100 pc compared to < 10 pc for GCs).

- Velocity dispersions for dSphs are ~ 10 km s^{-1}

- The closest is the Sagittarius Dwarf galaxy (25 kpc away), which is falling into the Milky Way and will be disrupted and stars incorporated in the disk.

- Other small companion galaxies have distances in the range $50 - 300$ kpc.

- New dwarf galaxies are still being discovered occasionally – the latest was in 2003 (Canis Major dwarf galaxy).

- They are surprisingly hard to see (particularly if behind the Milky Way disk).
- There are also ~ 200 globular clusters (examples 47 Tucanae, Omega Centauri) orbiting around the Milky Way in a roughly spherical halo.

The Local Group: Introduction

The Milky Way (+satellites) are part of a small group of galaxies – known as the *Local Group* – 36 galaxies at latest count.

Most massive components – the Andromeda spiral (M31) and the Milky Way.

A working definition of the Local Group are those galaxies that lie within 1 Mpc of the Milky Way.

The Andromeda Spiral and Companion Galaxies

M31 is 750 kpc away, and is $\sim 50\%$ more luminous than the Milky Way.

M31 also has a number of satellite galaxies (> 10).

The Whirlpool galaxy (M33, NGC598 – Sc), which is about one-fifth as bright as the Milky Way.

M32 (NGC221 – E3) is a small elliptical galaxy also associated with M31.

Other Galaxies

Apart from these, there are some galaxies which do not seem to be satellites of either M31 or the Milky Way – these are all dwarf galaxies

Examples include NGC 6822 and IC10.

The Mass of the Milky Way

There are good estimates of the enclosed mass of the Milky Way within different radii.

It is not known where the halo of the Milky Way finally fades out (or even if the size of the halo is a very meaningful concept).

The only way to get at the *total* mass of the Milky Way is to observe its effect on other galaxies.

The simplest but most robust of these comes from an analysis of the mutual dynamics of the Milky Way and M31.

The observational inputs are

1. M31 is ~ 750 kpc away,
2. the Milky Way and M31 are approaching at ~ 120 km/sec.

Simple approximation: Suppose that these two galaxies started out from roughly the same point with initial recessional velocities from the Big Bang, and have since turned around because of mutual gravitational attraction.

This is not strictly true of course, because galaxies had not already formed at the Big Bang.

It is thought that galaxies (at least galaxies like these) formed early in the history of the Universe, so the approximation may be acceptable.

It is likely that the material that ended up in the two galaxies emerged from the Big Bang and started off on a radial orbit moving away from each other, but then acquired angular momentum due to tidal torques from nearby galaxies while still in the proto-galactic stage.

Method is believed to give robust results for the total mass of Local Group (Li & White 2008).

Writing l for the distance and M for the combined mass in the Milky Way and in M31, the equation of motion for the reduced Keplerian one-body problem is

$$\frac{d^2 l}{dt^2} = -\frac{GM}{l^2} + \frac{L^2}{l^3}, \tag{6.1}$$

where L is the angular momentum of the system.

It is not obvious how to solve this nonlinear equation, but fortunately the solution is known and easy to verify; it is most conveniently expressed in parametric form, as

$$t = \left(\frac{a^3}{GM}\right)^{\frac{1}{2}} (\eta - e \sin \eta) \tag{6.2}$$

$$l = a\,(1 - e \cos \eta) \tag{6.3}$$

where e is the eccentricity of the orbit.

Here a is an integration constant,

$$a = \frac{L^2}{GM(1 - e^2)} \tag{6.4}$$

representing the semi-major axis of the orbit, the other integration constant has been eliminated by the boundary condition $l = 0$ at $t = 0$.

In considering a Keplerian problem without perturbation we are assuming that the gravity from Local Group dwarfs and the cosmological tidal field is negligible; but as there are no other large galaxies within a few Mpc this seems a fair approximation.

We assume that the angular momentum of this system is zero, so that $e = 1$.

Consider the dimensionless quantity

$$\left(\frac{t_0}{l_0}\right)\left(\frac{dl}{dt}\right)_{t_0} = \left(\frac{t_0}{l_0}\right)\left(\frac{dl}{d\eta}\frac{d\eta}{dt}\right)_{t_0} = \frac{\sin \eta_0 (\eta_0 - \sin \eta_0)}{(1 - \cos \eta_0)^2}, \tag{6.5}$$

where the subscripts in t_0 and so on refer to the current time, as conventional in cosmology.

Inserting the observed values for l_0 and $(dl/dt)_{t_0}$ and a plausible value of 12 Gyr for t_0 (the age of the Universe), we get -1.9 for the LHS.

To get the same value on the RHS we need $\eta_0 = 4.2$.

Using these values in eqn. (6.2) and (6.3) we get

$$M \sim 4 \times 10^{12} M_\odot. \tag{6.6}$$

The Future of the Milky Way

From its luminosity and rotation curve, M31 appears to have a mass 2$\times$ that of the Milky Way.

This implies that the mass of Milky Way exceeds $10^{12}M_\odot$.

Estimates of the luminous part of the Milky Way is about $1.5 \times 10^{10}L_\odot$, which implies that the mass-to-light ratio of the Milky Way is $M/L \sim 80M_\odot/L_\odot$, which is *much* higher than the typical values for spiral galaxies.

However, other determinations come from rotation curves (i.e enclosed mass). This implies that a lot of the mass of the Milky Way lies at large radii and is from dark matter.

Finally, the two galaxies are expected to collide when $\eta = 2\pi$, which turns out to be in about 3 Gyr.

Of course, if there is significant angular momentum in the system, the two galaxies will not collide.

There is the potential to work this out in near future (with GAIA).

Even if they do, the individual stars will not collide with each other, but the gas components will.