6. The Milky Way

The Milky Way is, as far as we know, a typical disc galaxy. Figure 6.1 is a cartoon to remind you of the different components of the Milky Way. The luminous parts are mostly a disc of Pop I stars and a bulge of older Pop II stars. We live in the disc, about 8.5 kpc from the centre. Apart from stars, the disc also has clusters of young stars and H II regions, and dust and gas; the gas is mostly observed as an H I layer which flares at large radii. There is some evidence that there are two spiral arms in the disc (the dust makes it hard to tell). The bulge has a bar, though the dimensions of it are unclear. But the most massive part is the halo; there are some old stars (and globular clusters of very old stars) in the halo, but most of the halo is dark matter of unknown composition.

That is not all: there are also the small companion galaxies. The best known of these are the the Large and Small Magellanic Clouds (LMC and SMC) which are $\simeq 50$ kpc away; these may or may not be part of a trail of debris known as the Magellanic Stream. Then there is the Sagittarius Dwarf galaxy which seems be to being sucked into the Milky Way halo now.

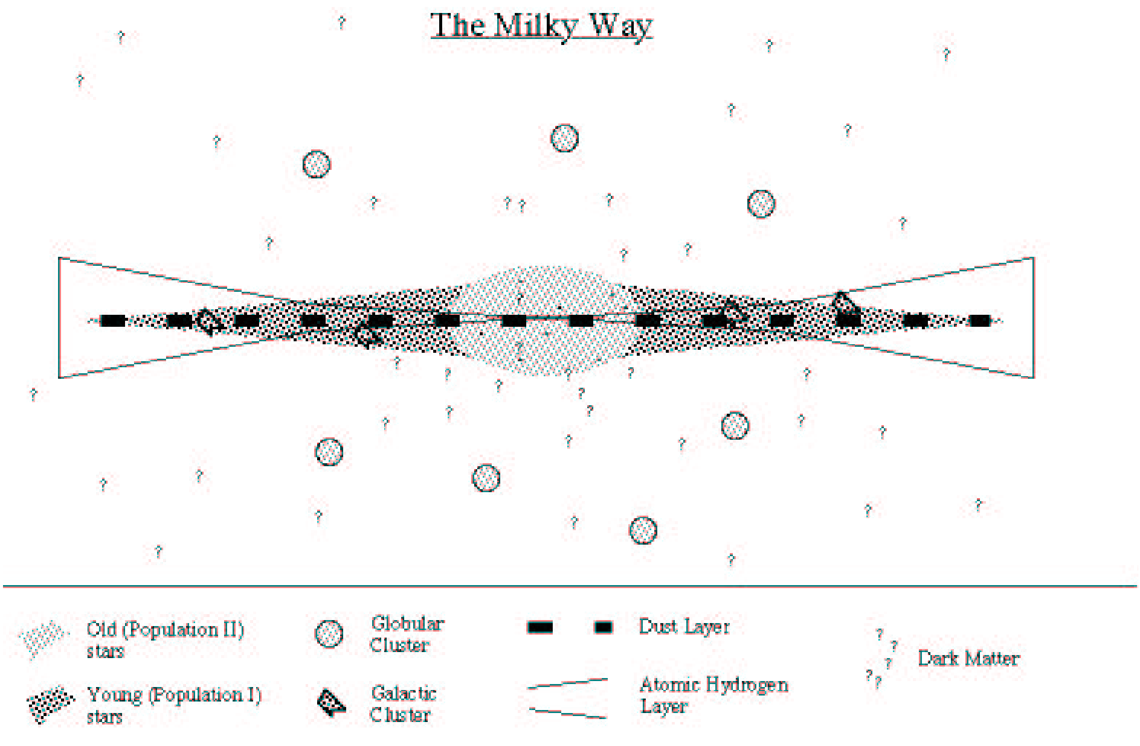

Figure 6.1: Cartoon of the Milky Way (by Mike Merrifield).

The mass of the Milky Way

While there are good estimates of 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). So 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 (Andromeda); it is known as the timing argument.

The observational inputs are (i) M31 is $\simeq 750\,\mathrm{kpc}$ away, and (ii) the Milky Way and M31 are approaching at $\simeq 120\,\mathrm{km/sec}$. A simple approximation for their dynamics is to suppose that they started out at the same point with initial recessional velocities from the Big Bang, and have since turned around because of mutual gravity. This is not strictly true of course, because galaxies had not already formed at the Big Bang; however it is thought that galaxies (at least galaxies like these) formed early in the history of the universe, so the approximation may be acceptable. Writing l for the distance and M for the combined mass in the Milky Way and in M31, the equation of of motion for the reduced Keplerian one-body problem is

$$\frac{d^2 l}{dt^2} = -\frac{GM}{l^2}. \tag{6.1}$$

In considering a Keplerian problem without perturbation we are, of course, 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. 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

$$\begin{aligned} t &= \tau_0(\eta - \sin\eta), \\ l &= \left(GM\tau_0^2\right)^{\frac{1}{3}}(1 - \cos\eta). \end{aligned} \tag{6.2}$$

Here τ_0 is an integration constant, the other integration constant has been eliminated by the boundary condition $l(t=0) = 0$. Now consider the dimensionless quantity

$$\left(\frac{t_0}{l_0}\right)\left(\frac{dl}{dt}\right)_{t_0} = \frac{\sin\eta_0(\eta_0 - \sin\eta_0)}{(1-\cos\eta_0)^2}, \tag{6.3}$$

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 $15\,\mathrm{Gyr}$ for t_0 (the age of the universe), we get -2.4 for the left hand side. The solution for η_0 to give the same value on the right hand side is 4.3. Inserting these values in (6.2) we get $\tau_0 = 2.9\,\mathrm{Gyr}$ and[1]

$$M \simeq 4 \times 10^{12} M_\odot. \tag{6.4}$$

From its luminosity and rotation curve, M31 appears to have of order twice the mass of the Milky Way. This implies that the mass of Milky Way exceeds $10^{12} M_\odot$. Estimates for the mass of the luminous part of the Milky Way range from 0.05 to $0.12 \times 10^{12} M_\odot$.

[1] It is useful to remember G in useful astrophysical units as $4.98 \times 10^{-15}\, M_\odot^{-1}\,\mathrm{pc}^3\,\mathrm{yr}^{-2}$.