Chapter 7

The Galaxy: Its Structure and Content

7.1 Introduction

Chapter 1 included a brief overview of our Galaxy, while later chapters discussed important processes affecting the Galaxy and other galaxies. Here we bring these concepts together to develop an understanding of the Galaxy itself. This will include a consideration of each of the components (disc, bulge, halo, etc.) in detail.

The Milky Way Galaxy is, as far as we know, a typical disc galaxy. Figure 1.8 was a cartoon to remind you of its different components. The luminous parts are mostly a disc of population I stars and a bulge of older population II stars. We live in the disc, with the Sun at a distance $R_0 = 8.0$ kpc from the centre. There is also gas and dust: the gas is mostly observed as an HI layer which flares at large radii. There are HII regions and clusters of young stars. There is some evidence that there are three or four spiral arms in the disc (the dust makes it hard to tell the number). The bulge is accompanied by a bar, though the dimensions of it are unclear. There are some very old stars (and globular clusters of very old stars) in the stellar halo. But the most massive part is the dark matter halo, which is made of 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 are associated with a trail of debris, mostly HI gas, known as the Magellanic Stream. Then there is the Sagittarius Dwarf Galaxy which appears to be merging with the Milky Way now.

7.2 The Mass of the Galaxy

The mass of the Galaxy enclosed within different radii can be determined using a variety of methods. Observations of the rotation curve provide measurements out to $\simeq 12 - 15$ kpc. Measurements of the dynamics of globular clusters can constrain the enclosed mass to a greater distance.

However, while 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). 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 (the Great Andromeda Galaxy): it is known as the timing argument. This is discussed in the next section.

7.3 The Mass of the Galaxy from Dynamical Timing Arguments

The dynamical timing argument relies on modelling the dynamics of the Galaxy and nearby galaxies. The Local Group contains two substantial spiral galaxies, the Galaxy and M31 (it does also contain one less massive spiral, M33, several irregular galaxies of modest mass, and numerous low mass dwarfs). We shall first consider the mass constraint that can be obtained from the dynamics of M31 and the Galaxy, ignoring the other Local Group galaxies.

The observational inputs are (i) M31 is $750\,\mathrm{kpc}$ away, and (ii) the Milky Way and M31 are approaching at $121\,\mathrm{km\,s^{-1}}$. (The transverse velocity of M31, if any, is poorly determined at present.) A simple approximation for their dynamics is to suppose that they started out at the same point moving apart with initial 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 of M31 from the Galaxy, and M for the combined mass of both systems, the equation of of motion for the reduced Keplerian one-body problem is

$$\frac{\mathrm{d}^2 l}{\mathrm{d}t^2} = -\frac{GM}{l^2} \ . \tag{7.1}$$

Here we shall count time from the Big Bang, so that $t = 0$ refers to the Big Bang. The current time and separation are t_0 and l_0.

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 solutions are well known and easy to verify. There are actually three solutions, depending on the precise circumstances. One solution applies to the case where the combined mass M is too small to halt the expansion and the two galaxies drift further apart for ever: this is not the case we have here. A second solution applies to the limiting case where the mass is just insufficient to stop the motion apart (so $\mathrm{d}l/\mathrm{d}t \to 0$ and $l \to \infty$ as $t \to \infty$). The third solution applies to the case where the mass is great enough to halt the drift apart and the galaxies fall back toward each other: it is this case that we have here, where the two galaxies are already falling towards each other.

This solution is most conveniently expressed in parametric form, as

$$t = \tau_0 \left(\eta - \sin \eta \right) \ ,$$
$$l = \left(GM\tau_0^2 \right)^{\frac{1}{3}} \left(1 - \cos \eta \right) \ . \tag{7.2}$$

Here τ_0 is an integration constant. The other integration constant has been eliminated by the boundary condition that the two galaxies (or at least the material from which
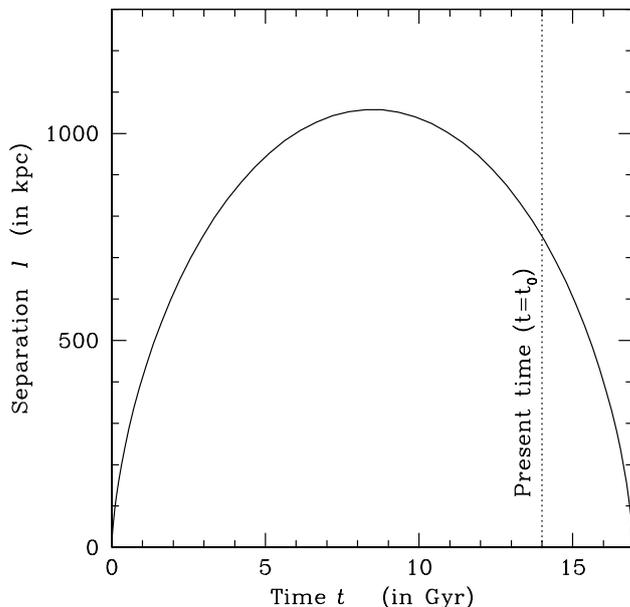
Figure 7.1: The change in the separation l of the Galaxy and M31 with time t since the Big Bang in the model used for the timing argument.

they formed) were at the same position immediately after the Big Bang: i.e. $l = 0$ at $t = 0$.

It is easy to show that these equations for t and l are a solution to Equation 7.1 by differentiating them to get $\mathrm{d}^2l/\mathrm{d}t^2$ and substituting them into Equation 7.1. This can be done using

$$\frac{\mathrm{d}^2l}{\mathrm{d}t^2} = \frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{\mathrm{d}l}{\mathrm{d}t}\right) = \frac{\mathrm{d}}{\mathrm{d}\eta}\left(\frac{\mathrm{d}l}{\mathrm{d}t}\right)\cdot\left(\frac{\mathrm{d}t}{\mathrm{d}\eta}\right)^{-1} = \frac{\mathrm{d}}{\mathrm{d}\eta}\left(\frac{\mathrm{d}l}{\mathrm{d}\eta}\left(\frac{\mathrm{d}t}{\mathrm{d}\eta}\right)^{-1}\right)\cdot\left(\frac{\mathrm{d}t}{\mathrm{d}\eta}\right)^{-1}$$

To determine the total mass M, we first consider the dimensionless quantity

$$\left(\frac{t_0}{l_0}\right)\left(\frac{\mathrm{d}l}{\mathrm{d}t}\right)_{t_0} = \frac{\sin\eta_0\,(\eta_0 - \sin\eta_0)}{(1 - \cos\eta_0)^2}\quad, \tag{7.3}$$

where the subscripts in t_0 and so on refer to the current time, as is conventional in cosmology. The quantity on the left-hand side can be calculated directly from observational data. Inserting the observed values of $l_0 = 750\,\mathrm{kpc}$ and $\left(\frac{\mathrm{d}l}{\mathrm{d}t}\right)_{t_0} = -121\,\mathrm{km\,s^{-1}}$ and a plausible value of $14\,\mathrm{Gyr}$ for t_0 (the age of the Universe), we get

$$\frac{\sin\eta_0\,(\eta_0 - \sin\eta_0)}{(1 - \cos\eta_0)^2} = -2.32\quad.$$

This equation can be solved numerically to give $\eta_0 = 4.28$. Inserting these values into $t_0 = \tau_0(\eta_0 - \sin\eta_0)$ from Equation 7.2, we get the constant $\tau_0 = 2.70$ Gyr. Then $l_0 = (GM\tau_0^2)^{1/3}(1 - \cos\eta_0)$ gives $(GM\tau_0^2)^{1/3}$, and using the value we found for τ_0 gives[1]

$$M \simeq 4.4 \times 10^{12} M_\odot\quad. \tag{7.4}$$

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

From its luminosity and rotation curve, M31 appears to have approximately twice the mass of the Milky Way, i.e. $M_{\mathrm{M31}} \simeq 2M_{\mathrm{Galaxy}}$. Using $M = M_{\mathrm{M31}} + M_{\mathrm{Galaxy}}$, 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 $(0.05 - 0.12) \times 10^{12}M_{\odot}$, which confirms that the majority of the mass of the Galaxy is unseen (it is dark matter).

It should be noted that this analysis predicts that the Galaxy and M31 will collide, and consequently merge, at some time, about 3.0 Gyr in the future. However, it fails to take account of the component of the velocity of M31 tangential to our line of sight. M31 and the Galaxy may have a tangential component, and therefore may have enough angular momentum that they may not actually come together.
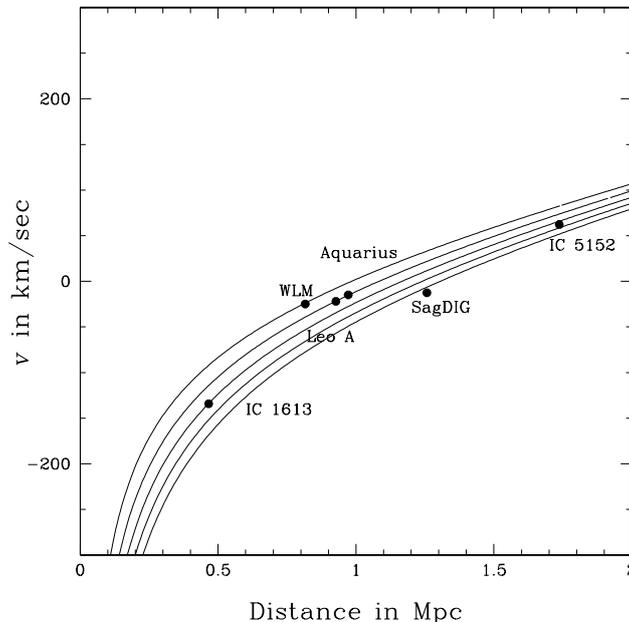

Figure 7.2: Distances and velocities of six Local Group dwarf galaxies, and predictions for different values of GM/τ_0 (by Alan Whiting).

The timing argument can be applied not only to the Andromeda Galaxy, but also to Local Group dwarf galaxies (which have much less mass and behave just as tracers). Figure 7.2 shows plots of l against $\mathrm{d}l/\mathrm{d}t$ for some Local Group dwarfs, along with the predictions of the timing argument for different values of GM/τ_0. This uses

$$l = \left(GM\tau_0^2\right)^{\frac{1}{3}}(1 - \cos\eta) \qquad \text{and} \qquad \frac{\mathrm{d}l}{\mathrm{d}t} = \left(\frac{GM}{\tau_0}\right)^{\frac{1}{3}}\frac{\sin\eta}{1 - \cos\eta} \ . \qquad (7.5)$$

This model assumes that the dwarfs have been moving on radial trajectories since the Big Bang.

7.4   Kinematics in the Solar Neighbourhood

The Milky Way is a differentially rotating system. The *local standard of rest* (LSR) is a system located at the Sun and moving with the local circular velocity (which is $\simeq 220\,\mathrm{km\,s^{-1}}$). The Sun has its own peculiar motion of $\simeq 13\,\mathrm{km\,s^{-1}}$ with respect to the LSR.

The rotation velocity and its derivative at the solar position are traditionally expressed in terms of Oort's constants:

$$A \equiv \frac{1}{2}\left(\frac{\langle v_\phi\rangle}{R} - \frac{\partial\langle v_\phi\rangle}{\partial R}\right) \qquad \text{at } R = R_0$$

$$B \equiv -\frac{1}{2}\left(\frac{\langle v_\phi\rangle}{R} + \frac{\partial\langle v_\phi\rangle}{\partial R}\right) \qquad \text{at } R = R_0 \qquad (7.6)$$

Observations show that $A = +14.4 \pm 1.2$ km s^{-1} (kpc)$^{-1}$ and that $B = -12.0 \pm 2.8$ km s^{-1} (kpc)$^{-1}$.

One reason that these parameters are useful is that A vanishes for solid body rotation (i.e. $A = 0$ when the angular velocity $\Omega(R) = \langle v_\phi\rangle/R = $ constant). Another useful property is that the gradient of the rotational velocity is $\partial\langle v_\phi\rangle/\partial R = -(A+B)$ at $R = R_0$, which means that $A + B = 0$ if the rotation curve is flat (because $\langle v_\phi\rangle$ is nearly the same as v_{circ}, and therefore we have $\partial\langle v_\phi\rangle/\partial R = \partial v_{circ}/\partial R = 0$ for $v_{circ} = $ constant). Therefore calculating $A + B$ is a test of whether the Galaxy has a flat rotation curve close to the Sun's distance from the Galactic Centre. Similarly, the angular velocity in the solar neighbourhood is $\Omega_0 = \langle v_\phi\rangle/R|_{R=R_0} = A - B$. (Note that $\langle v_\phi\rangle$ has been used in this paragraph, but the Oort analysis assumes that stars and gas move in perfectly circular orbits, and therefore at any point in the Galactic disc all material has the same v_ϕ. Therefore there was no need to call it $\langle v_\phi\rangle$.)

The radial and tangential components of the velocity of stars or gas in circular orbit, v_r and v_t, can be written as functions of the galactic longitude l as

$$v_r \simeq A\,d\,\sin(2l)$$
$$v_t \simeq A\,d\,\cos(2l) + B\,d \qquad (7.7)$$

locally (within about 1 kpc), where d is the distance from the Sun. (Note that the term 'radial' here means the component along the line of sight, not in the R coordinate direction.)

The advantage of the Oort constants A and B is that they describe the motions of stars around the Sun in the Galaxy, and they can be measured from simple velocity and distance data. But now that we have accurate proper motions from the Hipparcos satellite mission, and hence (combining with ground-based line-of-sight velocities) three-dimensional stellar velocities in the solar neighbourhood, A and B are less important.

If you take the average (three-dimensional) velocity and dispersions of any class of stars in the solar neighbourhood, then $\langle v_R\rangle$ and $\langle v_z\rangle$ turn out to be nearly zero, while $\langle v_\phi\rangle$ is such that $\langle v_\phi\rangle - v_{\text{LSR}}$ is negative and $\propto \sigma_R^2$. This is known as the *asymmetric drift* and essentially expresses the degree of rotational support versus pressure support. Young stars are almost entirely supported by $\langle v_\phi\rangle$, like the gas that produced them. The asymmetric drift v_a for young stars is therefore nearly zero, because $\langle v_\phi\rangle \simeq v_{\text{LSR}}$. Older stars pick up increasing amounts of pressure support in the form of σ_{RR}; they then need less v_ϕ to support them, and thus tend to lag behind the LSR. The linear relation can be derived from the Jeans equations, but we won't go through that because you've probably had enough of Jeans equations for now. . .

When examined in detail using proper motions from the Hipparcos astrometry satellite, the velocity structure in the solar neighbourhood is more complicated than anyone expected. Figure 7.3 shows a reconstruction of the stellar (u, v) (i.e., radial
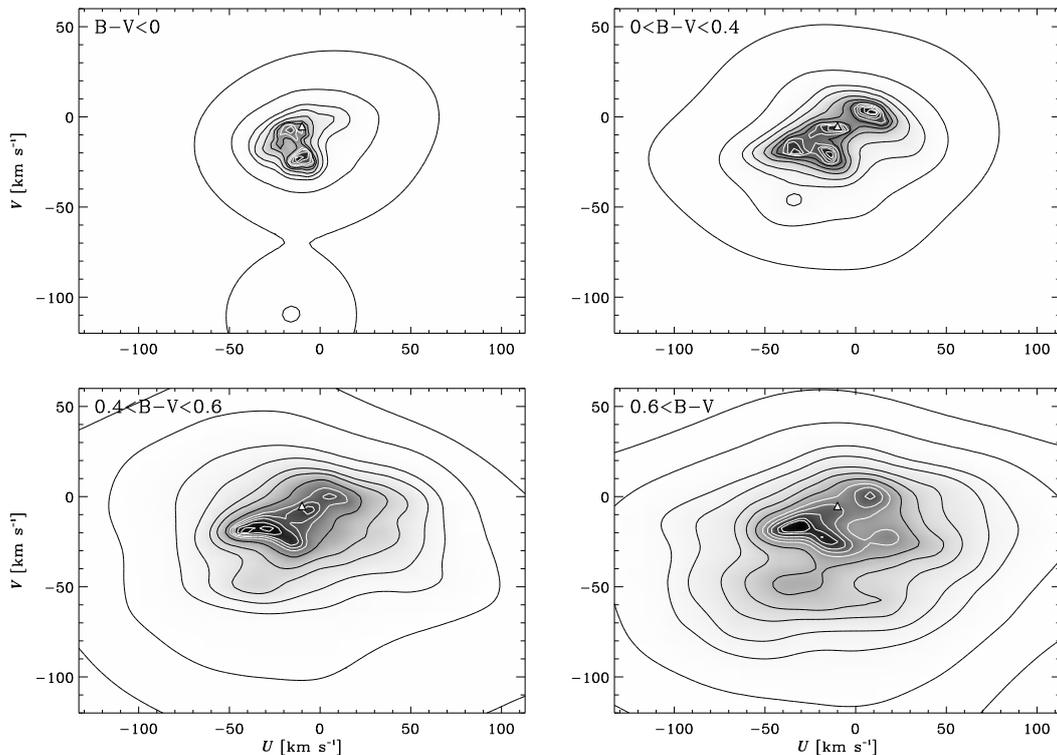
Figure 7.3: Distribution of radial (u) and tangential (v) velocities of main sequence stars in the solar neighbourhood, reconstructed from Hipparcos proper motions by Walter Dehnen (1998). The upper left panel is for the youngest (and bluest) stars; these are estimated to be < 0.4 Gyr old. The upper right panel is for stars younger than 2 Gyr, and the lower left panel is for stars younger than 8 Gyr. The lower right panel shows the combined distribution for all main sequence stars. The Sun is at $(0,0)$ and the LSR is marked by a triangle.

and tangential velocity) distribution in the solar neighbourhood for stars in different ranges of the main sequence.[2] Notice the clumps in the velocity distribution which appear for stars of all ages. (And these are clumps only in velocity space, not in real space.) The idea that there are groups of stars at similar velocities is itself not new—it actually dates from the early proper motion measurements of nearly a century ago. But these 'streams' have generally been interpreted as groups of stars which formed in the same complex and were later stretched in real space over several galactic orbits. The surprising new finding is that the 'streams' are seen for stars of all ages, which indicates a dynamical origin; they seem to be wanting to tell us something interesting about Milky Way dynamics, but as yet we don't know what.

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[2]The Schwarzschild ellipsoid and its vertex deviation that you may find in textbooks should now be considered obsolete—they are essentially the result of washing out the structure in Figure 7.3.

7.5   Dynamics of the Galactic Disc

The orbits of stars in galaxies are, in general, not closed paths, as we saw in Chapter 2. This is equally true of stars in the disc of our Galaxy. The tangential (v_ϕ) component dominates for disc stars (v_ϕ is much larger than the v_R and v_z components). We can therefore break the motion of disc stars into two parts: a uniform motion about the Galactic Centre, plus the motion relative to this uniform rotation. This second part is called an *epicycle*. The epicycle is very nearly an ellipse, but the period of the motion around the epicycle is not the same as the period of the uniform component of the motion. (The term epicycle was used historically for the complicated system of cycles that was used to fit the motion of the planets before Kepler explained the elliptical orbits about the Sun.)
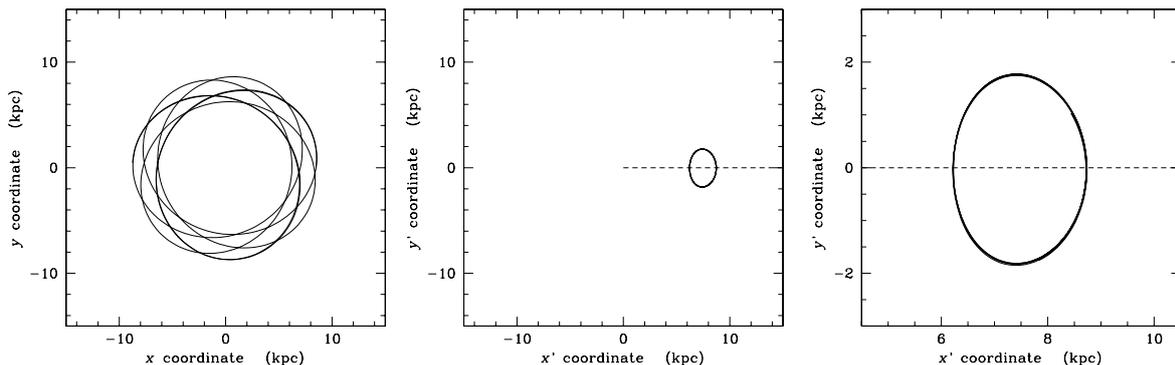

Figure 7.4: Epicyclic orbits. The first diagram shows the orbit of a star in a non-circular orbit in the disc of a spiral galaxy as viewed in an inertial (non-rotating reference) frame. It moves in a "rosette" pattern. The middle diagram shows the same orbit as viewed in a rotating frame, with the frame rotating with uniform motion and with a period equal to the orbital period of the star. The third diagram show the orbit of the star in the centre diagram in greater detail, showing the epicyclic motion.

7.6   The Disc (or Thin Disc)

The disc of the Galaxy contains mostly stars, with some gas. The stars are distributed with an exponential density profile in both the R and z directions. The density $\rho(R, z)$ is therefore described by

$$\rho(R, z) \;=\; \rho_0 \, e^{-R/h_R} \, e^{-|z|/h_z} \;\;,$$

where h_R and h_z are the scale lengths in the R and z directions, and ρ_0 is a constant. Observations show that $h_R \simeq 3.5$ kpc. The vertical scale height h_z is different for different age stars – young stars have smaller scale heights – but $h_z = 250$ pc is a typical value.

The disc is rotationally supported with a circular velocity $v_{circ} \simeq 220$ km s^{-1} at the Sun's position from the centre. There is a small velocity dispersion around this of 15 km s^{-1} for young stars, 40 km s^{-1} for old ones. Young stars form in the gas and naturally have a small velocity dispersion about the mean rotation. The greater velocity dispersion of older stars has probably been caused by perturbations of the stars

during encounters with giant molecular clouds. We learnt in Chapter 2 that stars are collisionless in galaxies. However, encounters between stars and giant molecular clouds can perturb stellar velocities in galactic discs to a limited degree over the lifetime of a spiral galaxy.

Heavy element abundances in disc stars are close to the solar values. Typical metallicities are [Fe/H] $= -0.4$ to $+0.2$.

The gas and its associated dust are concentrated close to the Galactic plane. The gas moves in circular orbits. The H I gas layer flares and warps at large radius.

The main disc is often called the *thin disc* to distinguish it from the thick disc, described below.

7.7 The Thick Disc

The term *thick disc* is usually given to a distribution of stars that is more extended in the vertical direction (perpendicular to the plane) than the main Galactic disc (the thin disc). The term is associated with stars, not gas. It consists of moderately metal-poor, older stars, with [Fe/H] close to -0.6. The system is rotationally supported, but $\langle v_\phi \rangle$ is slightly smaller than for the thin disc, a consequence of the stars showing a velocity dispersion that is larger than for those of the thin disc. The asymmetric drift $v_a = \langle v_\phi \rangle - v_{circ}$ is $30 - 50\,\mathrm{km\,s^{-1}}$ in magnitude. Only about 2% of the stars in the solar neighbourhood belong to the thick disc. The density distribution, like that of the thin disc, is a double exponential function, with probably a comparable radial scale length to the thin disc, but the vertical scale height is $h_z \simeq 1.3\,\mathrm{kpc}$. There has been some controversy over whether it is a distinct component of the Galaxy in its own right, or is made merely out of a small number of disc stars with extreme metallicities and kinematics.

7.8 The Bulge

The bulge is a spheroidally distributed, but flattened, system in the central regions of the Galaxy, confined to the inner 2 kpc. Its stars are old. They show a very wide range in metallicity, ranging from [Fe/H]$= -1$ to $+1$. It is largely pressure supported.

7.9 The Bar

There is little doubt now that the distribution of stars in the region of the Milky Way bulge is triaxial – there is a (rotating) bar with the positive l side nearer to us and moving away. The evidence for this was at first indirect, and took the following form. Consider gas in the ring, which must move on closed orbits. If this gas moved on circular orbits in the disc, and we measured its Galactic longitude l and line of sight velocity v, then all the gas at positive l (i.e. on one side of the Galactic Centre) would have one sign for v and similarly all the gas at negative l (on the other side) would have the opposite sign for v. In fact gas at positive l is seen with both signs for v, and likewise at negative l. So the gas orbits must be non-circular, and hence the gravitational potential must be non-circular in the disc. This suggests a bar and indeed the observed gas kinematics is well fitted by a bar.
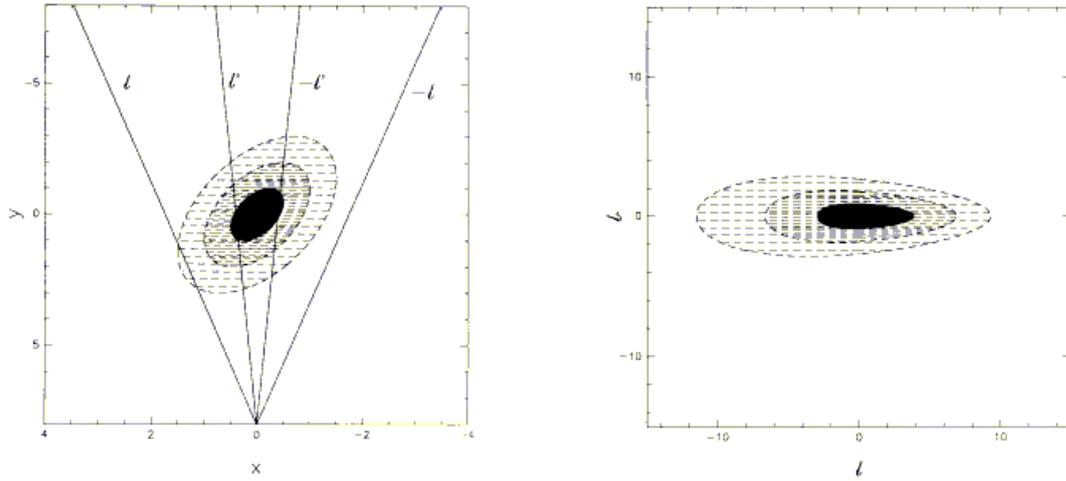
Figure 7.5: Schematic of the bar in the Milky Way Bulge, viewed from the North Galactic pole (left), and from the Sun (right). (From Blitz and Spergel, *ApJ*, 1991. The right panel uses minus the usual convention for *l*.)

The features of a bar can in fact be seen in an infrared map of the bulge, if you know what to look for. Figure 7.5 shows a bar in the plane, and its effect on an l, b map.

1. The side nearer to us is brighter. Contours of constant surface brightness are further apart in both l and b on the nearer size.

2. Very near the centre, the *further* side appears brighter, so the brightest spot is slightly to the further size of $l = 0$. The reason is that on the further side our line of sight passes through a greater depth of bar material, which more than compensates for it being slightly further.

The features (i) can be discerned in many different data sets; the feature (ii) is harder to find, it just about shows up in the COBE maps of the bulge.

7.10   The Galactic Centre

Observing the centre of the Galaxy is extremely difficult in the optical because the extinction caused by dust in the Galactic plane is approximately 30 magnitudes in the V-band. Things are not so extreme in the infrared, and in the K band (2.2 μm) the extinction is a more moderate 3–4 mag. However, the available data show that there is a very dense star cluster at the Galactic centre, with a compact radio source, Sagittarius A* (abbreviated Sgr A*) at its centre. There is a ring or disc of gas around the centre, about 5 pc across, detected by its molecular emission.

Orbital velocities immediately around Sgr A* are very high. The available evidence suggests that there is a compact massive object at the centre of Sgr A*. This is probably a central black hole with a mass $1 - 3 \times 10^6 \, M_\odot$.

7.11 The Stellar Halo

The stellar halo is the spheroidally distributed, slightly flattened, system that extends far from the disc. It includes diffuse field stars and globular clusters. The stars are very old (13 Gyr) and are very metal-poor, having [Fe/H] $\simeq -1$ to -2.5. It makes only a very small contribution to the total mass of the Galaxy. It is a pressure-supported system. The velocity dispersion is $\sigma = 120$ kms^{-1}. The asymmetric drift is $\simeq 190$ km s^{-1} at the Sun's position. These two figures mean that the kinematics of halo stars are very different to those of the disc. Only about 1/1000-th of the stars in the solar neighbourhood belong to the halo. Examples of halo stars in the solar neighbourhood, of value for example in studying chemical abundances in very metal-poor stars, have often been found from their high proper motions: relatively nearby halo stars usually have large motions across the sky compared with typical (disc) stars.

7.12 Globular Clusters

The Galaxy contains about 150 globular clusters. They are compact systems of $\sim 10^5$ stars. Many of these are very metal-poor, are distributed spheroidally and have randomly orientated orbits: they appear to be associated with the stellar halo.

However, some globular clusters are only moderately metal-poor. Those globular clusters having [Fe/H]> -0.8 form a more flattened system. They may be associated with the thick disc.

7.13 The Dark Matter Halo

The dark matter halo appears to extend out to large radii, to $\gtrsim 100$ kpc, as is shown by studies of the dynamics of companion dwarf galaxies, for example. It dominates the mass of the Galaxy. It appears to be spheroidally distributed: it does not appear to be concentrated in the Galactic disc, as we saw in Section 2.22.

The nature of dark matter is unknown, but it appears not to be in the form of $\sim$ stellar mass compact objects, such as white dwarfs or brown dwarfs, as microlensing surveys have shown (at least only a small proportion of the dark matter can be in stellar mass compact objects). Neither is it likely to be in the form of dark compact objects having masses $\gtrsim 1000 M_{\odot}$, such as massive black holes. Objects of this type would perturb the dynamics of disc stars, thickening the disc, which is not observed on a significant scale.

Constraints from primordial nucleosynthesis imply that baryonic matter only contributes 4 % of the closure density of the Universe. Cosmological results indicate that matter contributes 27 % of the closure density. Therefore we expect that most of the dark matter in the Universe is not in the form of baryonic matter, if the cosmological models are correct. This is consistent with the results of Galactic microlensing surveys.

The dark matter must be composed of individual particles, be they subatomic particles or astronomical bodies. To support a spheroidal distribution within the Galaxy's potential, these particles must be moving on mostly randomly orientated trajectories with a velocity dispersion of $100 - 400$ km s^{-1}. The dark matter particles do not dissipate significant energy in interactions with each other (or with the luminous matter), otherwise it would settle down to a rotating disc or a single mass at the centre

of the Galaxy's potential – which it has not done.

7.14   The Local Group

The Galaxy lies in a system of more than 40 galaxies called the Local Group, about 1 Mpc across. There are two large spiral galaxies – the Galaxy and the Great Andromeda Galaxy (M31) – and one spiral (M33) of slightly lower mass. There are a few irregular galaxies, most notably the Large Magellanic Cloud and the Small Magellanic Cloud, but these are not particularly massive. All the other members are dwarf galaxies, either dwarf irregulars, dwarf ellipticals or dwarf spheroidals.

A large majority of the galaxies are companions of either the Galaxy or M31. For example, the Magellanic Clouds are situated $50 - 60$ kpc from the Galaxy. Several of the dwarf spheroidal galaxies lie within 200 kpc.

7.15   The Formation of the Galaxy

A fundamental question relating to the Galaxy is how it was formed. Some stars in the Galaxy, such as those in the thick disc and bulge, and particularly in the halo, are old. The oldest stars were formed relatively early in the history of the Universe, indicating that the Galaxy had a relatively early origin. Star formation has continued in the disc, at least, throughout its history.

There are two main scenarios for the formation of the Galaxy:

- the monolithic collapse model, and
- the merging of subunits.

The monolithic collapse model was developed in the 1960s, particularly by Eggen, Lynden-Bell and Sandage. In this picture, the Galaxy formed by the collapse of a protogalactic cloud of gas that had some net angular momentum. The gas initially had a very low metallicity. The collapse occurred mostly in the radial direction and some modest star formation occurred during this time. This produced very metal-poor stars with randomly-oriented elongated orbits, which today are observed as the stellar halo. The gas settled into a broad rotating disc, which was moderately metal-poor by this time as a result of the enrichment of the gas by the heavy elements created by halo stars. The rotation was the result of the net angular momentum of the protogalactic cloud. Star formation in this cooling, settling disc produced thick disc stars which are rotationally supported but have an appreciable velocity dispersion. The gas continued to settle into a thinner, stable, rotating disc. Residual gas that fell to the central regions formed the bulge stars. Star formation continued in the gas disc at a gradual rate, building up the stars of the thin disc.

This model predicted the main features of the Galaxy, and did so very neatly. It explained the fast rotation of disc stars with their near-solar metallicities, and the randomly orientated orbits of halo stars with their very low metallicities and great ages.

The merging scenario instead maintained that the Galaxy was built up by the merging and accretion of subunits. It was first developed by Searle and Zinn in 1977 for the stellar halo. The merging model is strongly supported by detailed computer simulations of galaxy formation. These simulations predict that the primordial material from the Big Bang clumped into large numbers of dark matter haloes that also

contained gas. These small haloes then merged through their mutual gravitational attraction, building up larger haloes in the process. The gas formed some stars in these dark matter clumps. A large number of these subunits produced our Galaxy, with the gas settling into a rotating disc as a natural consequence of the dissipative, collisional nature of the gas. Star formation in the disc then formed the disc stars. The stars of the Galactic stellar halo may have come from the accretion of subunits that had already formed some stars. This process of building galaxies by the merging of clumps to form successively larger and larger units is known as *hierarchical galaxy formation.*

Mergers certainly played an important role in the formation and subsequent evolution of the Galaxy. Detailed computer modelling of galaxy formation provides powerful evidence in favour of this picture. Indeed the merging process appears to be ongoing, as discussed in the following section.

7.16   The Sagittarius Dwarf

We end our discussion of the Galaxy with a brief mention of the Sagittarius Dwarf. Although originally an independent galaxy, it is now in the process of being pulled apart by the gravitational influence of our own Galaxy.

It may seem amazing that this fairly substantial companion galaxy of the Milky Way remained undiscovered until 1993. This is principally because of its location, behind the bulge, where it is partially obscured by the densest stellar and dust concentration in the Milky Way. This makes its dimensions difficult to estimate precisely. However a lower limit on its size comes indirectly from microlensing surveys, using RR Lyrae variables.

The Sagittarius Dwarf is a highly elongated body, by virtue of the ongoing tidal disruption by the Milky Way. It includes a number of globular clusters, including M54, and is associated with tidally-stripped star streams, as shown by the numerically simulated results shown in Figure 7.6. It contains mostly moderately old or very old stars and estimates suggest that it will be totally disrupted over the following 10^8–10^9 years, with its stars being incorporated into the Galaxy's stellar halo.

The Sagittarius Dwarf provides evidence that the Galaxy is actively accreting small companion galaxies. It may well have consumed many such galaxies in the past. Indeed, a recent study of infrared observations has found debris from a dwarf galaxy, which has been called the Canis Major Dwarf, situated within the Galaxy about 13kpc from the Galactic centre. Other star streams have now been found in the Galactic stellar halo, which are also probably the remnants of dwarf galaxies that have been tidally disrupted. This provides evidence that merging is a significant and ongoing process in galaxy evolution, as well as in the formation of galaxies.
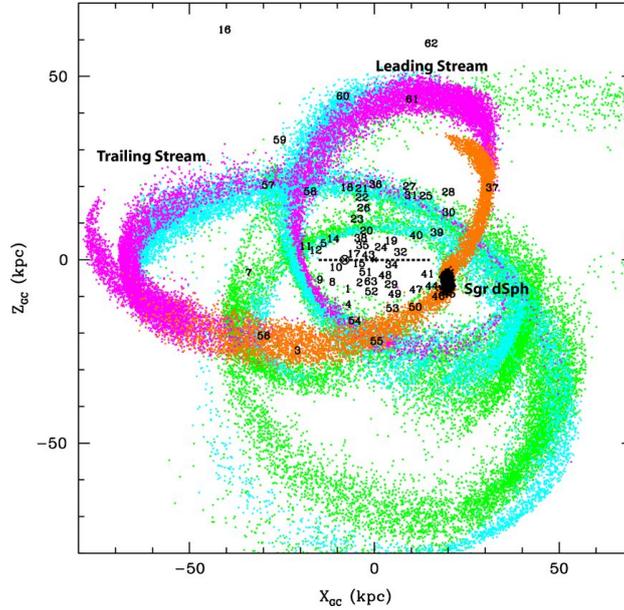
Figure 7.6: The results of a numerical simulation of the tidal disruption of the Sagittarius Dwarf system (coloured points) in Galactocentric Cartesian coordinates (XGC,ZGC) i.e. looking edge on to the galactic plane, with X as the horizontal axis and Z as the vertical axis, in kpc. The colour of individual debris particles represents the time at which the particle became unbound from the Sgr dwarf. The x indicates the location of the Galactic centre, while the circled x indicates the location of the Sun. The horizontal dashed line represents the Galactic disk plane, with length corresponding to a diameter of 30 kpc. Overplotted against the model are ID numbers corresponding to the locations in the XGC–ZGC plane of Milky Way stellar satellites (figure and adapted caption from Law & Majewski, 2010, Apj. 718:1128–1150).