Lecture 30 - Morphology of galaxies

What's Important:

- size and shape of galaxies
- distribution of masses

Text: Carroll and Ostlie, Chap. 22.1, 22.2, 22.4

Milky Way

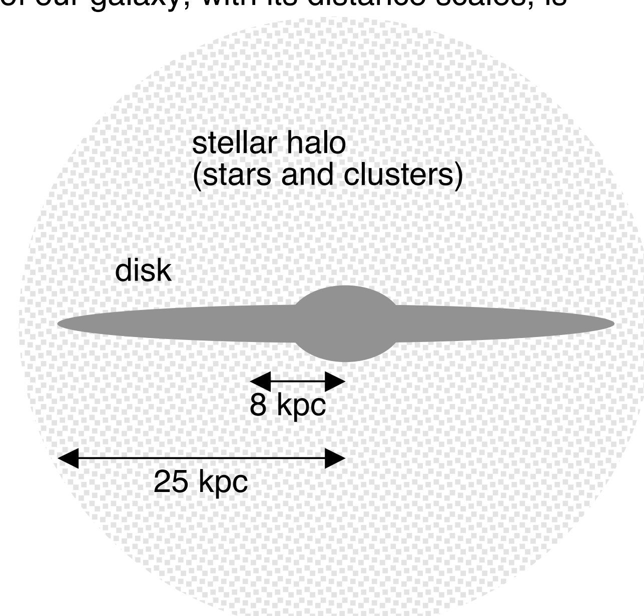
The galaxy in which we reside, the Milky Way, is a collection of about 10^{11} stars. From what we can now see of other galaxies, the structure of the Milky Way is probably not unusual, although we don't have an "external" picture of the galaxy taken from a remote vantage point. Amusingly, our view of the galaxy changes with time, as the orbit of the Sun is not in the plane of the galaxy: in 15 million years, the Sun will be sufficiently far from the galactic plane that we will have a view of the galactic centre, a view now blocked by dust etc.

Historical note (from Carroll and Ostlie):

With the invention of the telescope, Galileo recognized that the Milky Way is a vast collection of individual stars. It was first proposed by Immanuel Kant and Thomas Wright in the mid-1700s that the Milky Way is disk-shaped. In the 1780's William Herschel used a star count (with some assumptions) to conclude that the Sun is close to the centre of this disk. Performing an accurate star count is not an easy task because of the varying intrinsic magnitude, intervening dust clouds, etc., and it was not until the 20th century that many of these effects could be properly taken into account.

Our picture of the Milky Way

A modern side view of our galaxy, with its distance scales, is



Modern values for the dimensions are (1 pc = 3.26 ly):

radius = 25 kpc = 80,000 light years

Sun's position = 8.0 ± 0.5 kpc = 26,000 ly from centre.

Disk

The disk itself can be viewed as three components;

- young thin disk (current site of star formation), with a density falling to $1/e$ of its central value in 0.050 kpc
- old thin disk, falling to $1/e$ at 0.325 kpc = z_{thin}.
- old thick disk, falling to $1/e$ at 1.4 kpc = z_{thick}.

Stars are not uniformly distributed in the disk, but their number density n obeys

$$n(z,R) = n_o \, [\, \exp(-z/z_{\text{thin}}) \; + \; 0.02 \cdot \exp(-z/z_{\text{thick}}) \,] \cdot \exp(-R/h_R)$$

where z is the perpendicular displacement from the plane, R is the radial distance from the galactic centre, and h_R = 3.5 kpc. The number density at the centre, as given by n_o, is 0.02 stars / pc^3, for stars in the absolute magnitude range $4.5 \leq M_v \leq 9.5$.

The spectra of stars in the thin disk display a higher metal content, indicating that the stars contain material that has previously been processed through older stars - hence, the stars in the young thin disk are more recently condensed (or young). Based on stellar evolution models, the abundance of metals argues that the Milky Way itself is *not* young, but is perhaps 10-12 billion years old.

The thin disk contains about 6×10^{10} solar masses of stars, plus about 0.5×10^6 solar masses of dust *etc*. Although the thick disk extends further than its thin cousin, the prefactor of 0.02 in the relative density at $z = 0$ shows that it has far fewer stars (integrate to find how many).

Bulge

The central bulge has the shape of a bar or peanut, and contains about 10^{10} solar masses, or about 1/6 of the mass of the disk.

Halo

The halo contains both individual stars (*field stars*, often with high velocities), plus clusters. So far, more than 100 clusters have been identified, and perhaps 230 are thought to exist in total. The stellar density distribution obeys:

$$n_{\text{halo}}(r) = n_{o,\text{ halo}} \, (r \,/\, r_e)^{-3.5},$$

with r_e = 2.7 kpc $\qquad n_{o,\text{ halo}}$ = 0.2% of $n_{o,\text{ disk}}$.

Does the power-law behavior of the halo density stop at some point? Most clusters in the halo are found within a radius of 35 kpc of the centre, although a few lie beyond this cut-off.

We should not immediately dismiss the mass in the halo because of the small $n_{o,\ halo}$, because the halo covers a larger volume than the disk (integrate to find how many). The total visible mass of the halo as ~ 1 x 10^9 solar masses, of which 1% is in the form of globular clusters and the remainder is in field stars. The dark matter contribution to the halo may be much larger - 55 x 10^{10} solar masses, which would be about 8 times the visible mass of the disk and halo combined.

Mass to light ratio

The mass-to-light ratio in the thin disk, and the bulge, is given approximately by

$$M / L = 3\ M_{sun}/L_{sun}.$$

which can be rearranged to read

$$L / L_{sun} = (1/3)\ M / M_{sun}.$$

This specific ratio can be substituted into the general form (observation, not theory)

$$L / L_{sun} = (M / M_{sun})^4,$$

to obtain a measure of the mean mass of the light-producing stars in the disk or bulge, namely:

$$(1/3)\ M / M_{sun} = (M / M_{sun})^4,$$

or

$$M / M_{sun} = (1/3)^{1/3} = 0.7.$$

In other words, a typical stellar mass in these regions is a little less than our Sun.

Galactic centre

As the galactic centre is approached, the speeds of (identifiable) objects such as gas clouds rapidly increase, rising to 700 km/s at a distance of 0.1 pc from the centre. Carroll and Ostlie use an example of a gas cloud at 0.3 pc having a speed of 260 km/sec to determine the mass in this central region:

$$G\ m_{cloud}\ M_{central} / R^2 = m_{cloud} a_c = m_{cloud}\ v^2/R \qquad \text{(circular orbit)}$$

gives

$$M_{central} = v^2 R / G$$

or

$$M_{central} = (2.6 \times 10^5)^2 \cdot 0.3 \cdot 3.09 \times 10^{16} / 6.67 \times 10^{-11}$$
$$= 9.4 \times 10^{36} \text{ kg}$$
$$= 9.4 \times 10^{36} / 1.99 \times 10^{30} = 4.6 \times 10^6 \text{ solar masses.}$$

This corresponds to a density of stars of

$$M_{central} / (4\pi R^3/3) = 4.6 \times 10^6 / (4\pi\ 0.3^3 / 3) = 4 \times 10^7 \text{ pc}^{-3},$$

assuming one star per solar mass. Now, compared to n_o = 0.02 pc^{-3} in the mid-magnitude range of the galactic disk, this number is immense.

If this dense region corresponded to a supermassive black hole, what would be its radius? From general relativity, the Schwarzschild radius of a black hole of mass M is given by

$$R_{bh} = 2GM/c^2,$$

which yields

$$R_{bh} = 2 \cdot 6.67 \times 10^{-11} \cdot 5 \times 10^6 \cdot 1.99 \times 10^{30} / (3.0 \times 10^8)^2$$
$$= 1.5 \times 10^{10} \text{ m}$$
$$= 1.5 \times 10^7 \text{ km}$$
$$= 15 \text{ million km.}$$

Rather large for a black hole; in AU, this is

$$R_{bh} = 1.5 \times 10^7 \text{ km} / 1.5 \times 10^8 \text{ (km/AU)} = 0.1 \text{ AU},$$

in other words, 10% of the distance to the Sun.

Other galaxies

We finish off this aspect of our galactic tour by asking whether the Milky Way is an unusual galaxy, characterized as it is by

visible mass of 8×10^{10} solar masses (dark matter may add 55×10^{10})
diameter of 50 kpc.

Carroll and Ostlie provide a summary description of several classifications of galaxies (p. 1010 and 1011), confirming that the Milky Way is just another galaxy:

- early spiral galaxies 10^9 - 10^{12} solar masses 5 - 100 kpc diameters
- late spirals and irregulars 10^8 - 10^{10} solar masses 0.5 - 50 kpc diameters.