Astronomy 401/Physics 903
Lecture 2
Contents and structure of the Milky Way

1 What is a galaxy?

A collection of stars ($\sim 10^6$ to $\sim 10^{12}$, roughly), gas, dust and dark matter, held together by gravity. Bigger than a star cluster, smaller than a cluster of galaxies. (This question isn't entirely settled; see `http://arxiv.org/abs/1101.3309v2`) There are hundreds of billions of galaxies, but we'll start with an overview of our galaxy, the Milky Way.

2 Early observations

On a dark night, the Milky Way can be seen as a luminous band of light across the sky. This was called *galaktikos kuklos* in ancient Greek, meaning "milky circle;" this is the origin of the work "galaxy." Galileo observed the band to be made up of many individual stars. A hypothesis that explains the Milky Way is that the sun is embedded in a thin disk of stars; when we look perpendicular to the disk we see few stars and the sky is dark, while we see many stars when we look into the plane of the disk. This disk of stars is a major component of the galaxy.

3 Background: magnitudes

Necessary background for galactic and extragalactic astronomy: The **apparent magnitude** m is a logarithmic measure of the brightness of a star, dating from the Greek astronomer Hipparchus in the 2nd century BC—he classified all visible stars in six categories, with the brightest stars being 1st magnitude and the faintest 6th magnitude. This was put on a mathematical basis in the 19th century; a difference of 5 magnitudes is a factor of 100 in flux. So if

$$m_2 - m_1 = 5 \tag{1}$$

the ratio of the stars' fluxes is

$$\frac{F_1}{F_2} = 100 \tag{2}$$

(note that the magnitude scale is backwards: bigger numbers mean fainter things) and if $m_2 - m_1 = 1$, the ratio of fluxes is

$$\frac{F_1}{F_2} = 100^{1/5} = 10^{0.4} \approx 2.512. \tag{3}$$

The general relation between apparent magnitude and flux is

$$\frac{F_1}{F_2} = 100^{(m_2-m_1)/5} = 10^{0.4(m_2-m_1)} \tag{4}$$

or

$$m_2 - m_1 = 2.5\log(F_1/F_2). \tag{5}$$

The apparent magnitude is a logarithmic measure of the flux, with

$$m = C - 2.5\log F, \tag{6}$$

with the constant C historically chosen so that the star Vega (α Lyra) has an apparent magnitude of zero. Brighter stars have smaller magnitudes.

If we want to know the intrinsic luminosity of a star instead of how much flux we receive from it, which depends on its distance, we use the **absolute magnitude** M. The absolute magnitude of a star is defined as the apparent magnitude it would have if it were at a distance $d = 10$ pc. Can work this out, find that the relation between apparent and absolute magnitude is

$$m - M = 5\log(d/10\text{ pc}). \tag{7}$$

This is called the **distance modulus**.

The Sun has an apparent magnitude of -26.75 and an absolute magnitude of 4.83.

Magnitudes are often given in a particular bandpass; this is because we measure the brightness of a star in a particular wavelength range corresponding to the filter on our telescope, not its total luminosity at all wavelengths (the total luminosity is known as **bolometric luminosity**). Some common filters are B (blue), V (visible, which is green, more or less), R (red) and I (redder than R). Absolute magnitudes in these bands are written M_B, M_V, etc. Apparent magnitudes are written as B, V, etc.

4 The size and shape of the Galaxy from star counts

The first and simplest method of determining the size and shape of the Galaxy. Start with some simplifying assumptions:

- All stars have the same absolute magnitude M. Not generally true, but we can choose to look only at a particular type of star.
- The number density of stars n is constant within our Galaxy.
- There is no absorption of starlight by dust. (Dubious!)

A star of absolute magnitude M will have an apparent magnitude m when it is at a distance

$$d = 10^{0.2(m-M+5)}\text{ pc} \tag{8}$$

(this is just a rearrangement of the distance modulus[1]). Every star closer than d will be brighter than m. So the total number of stars brighter than m will be

$$N(<m) = \frac{4\pi}{3}d^3 n = \frac{4\pi}{3}10^{0.6(m-M+5)}n, \tag{9}$$

or

$$\log N = 0.6m + \text{ constant}. \tag{10}$$

By going 1 magnitude fainter you should increase the number of stars you see in a given patch of sky by a factor of $10^{0.6} \approx 4$.

Now suppose there are no stars beyond a distance $d_{\max}$. This will mean there are no stars fainter than $m_{\max}$, where

$$m_{\max} = M + 5\log d_{\max} - 5 \tag{11}$$

[1]The distance modulus is $m - M = 5\log(d/10\text{ pc})$, so $0.2(m-M) = \log(d/10)$, and $10^{0.2(m-M)} = d/10$. We solve for d: $d = 10 \cdot 10^{0.2(m-M)} = 10^{0.2(m-M)+1} = 10^{0.2(m-M+5)}$

(of course this requires that your survey is sensitive enough to detect stars fainter than $m_{\max}$ if they were there). So if we find $m_{\max}$ for a particular patch of sky, we can find $d_{\max}$ in that direction:

$$d_{\max} = 10^{0.2(m_{\max} - M + 5)} \text{ pc}. \tag{12}$$

This method was used to study the size and shape of the Galaxy by William and Caroline Herschel in the late 18th century, and more quantitatively by Jacobus Kapteyn in 1922. Both determined that the Sun was near the center of a small disk of stars approximately 5 times larger in diameter than it was thick.

Is this right? Why not? Dust!

5 Globular cluster distribution

Between 1915 and 1919, Harlow Shapley arrived at a better estimate of our place in the Milky Way using the distribution of globular clusters (compact, spherical clusters of old stars whose distances can be estimated because they contain variable stars whose periods depend on their absolute brightness—RR Lyrae stars, more on that later). Shapley noticed that globular clusters aren't distributed uniformly across the sky; instead they're concentrated in one half of the sky, centered on constellation Sagittarius. He concluded that the globular clusters were all orbiting the center of the galaxy, which lies in the direction of Sagittarius. He also measured the distances to the globular clusters to estimate the size of the galaxy; got it a bit wrong, since he thought that RR Lyrae stars were brighter than they are, but had the order of magnitude right. We are about 8 kpc from the center of the Milky Way.

We still use both star counts and the globular cluster distribution to study the Galaxy, with better understandings of dust absorption and distances.

6 Components of the Milky Way

The Galaxy has three basic components, the disk, halo and bulge. These can be further divided according to their age, shape or composition.

Table 1: Components of the Milky Way

Component	Mass (10^{10} M$_\odot$)	Luminosity (10^{10} L$_\odot$, B-band)	Diameter (kpc)
Thin disk	6	1.8	50
Thick disk	0.2–0.4	0.02	50
Neutral Gas	0.5	—	50
Bulge	1	0.3	2
Stellar halo	0.1	0.1	100
Dark matter halo	55	0	> 200
Central black hole	0.00037	—	—

(Mass of central black hole: $3.7 \pm 0.2 \times 10^6$ M$_\odot$)

6.1 The Disk of the Milky Way

- Most luminous component of Galaxy
- Radius ~ 25 kpc, stars to 15–20 kpc

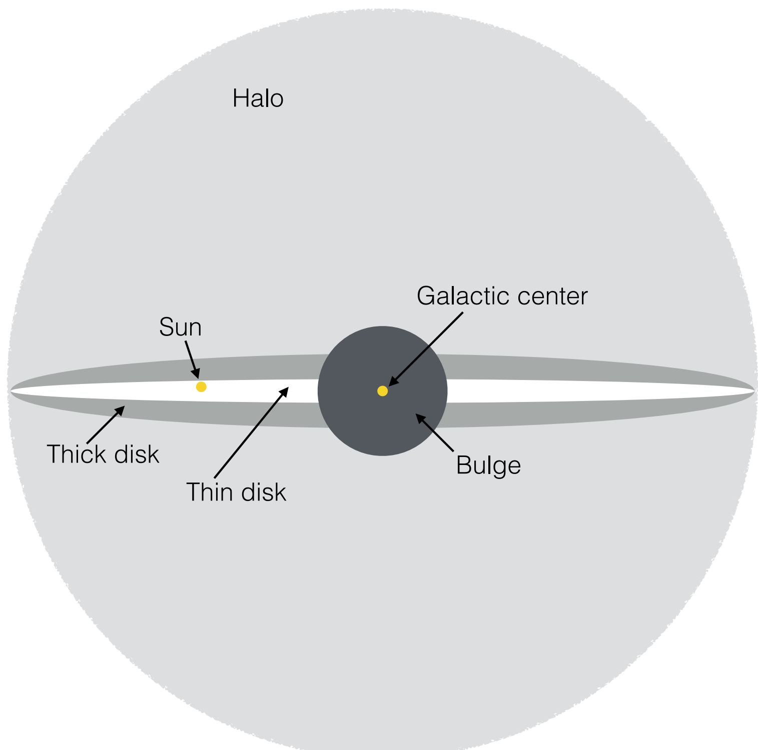

Figure 1: Schematic diagram of the primary components of the Milky Way. The diagram is not to scale; see the table below for characteristic properties of each component.

- Gas disk of galaxy, seen in emission from neutral hydrogen, extends further, to $R \sim 25$ kpc from the Galactic center
- Thickness of disk is small compared to its radius: most stars are less than 0.5 kpc from the midplane of the disk
- Studying stellar properties as a function of z, the distance from the midplane, shows that the disk can be further divided into two components: a **thin disk** containing stars of all ages including stars that are currently forming, and a **thick disk** made up of stars older than ~ 5 Gyr.
- Near the Sun, the distribution of stars in both the thin and thick disks falls exponentially with distance z from the midplane.
  - Thin disk: $n(z) = n_{\rm thin} \exp(-|z|/h_{\rm thin})$, where the scale height $h_{\rm thin} \approx 325$ pc and $n_{\rm thin}$ is the number density of thin disk stars at $z = 0$. (Scale height: the height at which the density drops by a factor of $e^{-1} \simeq 0.37$.)
  - Thick disk: $n(z) = n_{\rm thick} \exp(-|z|/h_{\rm thick})$, where the scale height $h_{\rm thick} \approx 1.5$ kpc.
  - In the midplane, $n_{\rm thin} \approx 10 n_{\rm thick}$.
  - Sun is member of the thin disk and is about 30 pc above the midplane.
- The disk shows spiral structure, with star formation concentrated in the spiral arms. We'll talk about this more when we discuss spiral galaxies.
- The disk also contains gas and dust. Gas mostly neutral hydrogen, and $M_{\rm dust}/M_{\rm gas} \simeq 0.007$.

6.2 Bulge

- Galaxy has a central bulge, about 1 kpc in radius, extending above and below the disk.
- Scale height ranges from 100 to 500 pc, depending on ages of stars measured. Younger stars have smaller scale heights.
- Tiny nucleus in the center, bright at radio wavelengths. More on that later.
- Difficult to observe because of large amounts of dust extinction.
- Contains a mixture of stars of different ages

6.3 Halo

- Roughly spherical distribution of stars
- Radius ~ 100 kpc
- Same luminosity as bulge, but volume $\sim 10^6$ times larger
- Old, low metallicity stars
  - Metallicity Z: fraction by mass of elements heavier than helium

- Can also measure the amount of a particular element X. This is written as the *metallicity index*:

$$[\mathrm{X/H}] \equiv \log\left(\frac{n(\mathrm{X})}{n(\mathrm{H})}\right) - \log\left(\frac{n(\mathrm{X})}{n(\mathrm{H})}\right)_\odot \tag{13}$$

  where $n(\mathrm{X})$ and $n(\mathrm{H})$ are the number densities of element X and hydrogen respectively. Example: a star with [Fe/H] $= -0.1$ has 1/10 of the Solar abundance of iron. (This definition is at the end of Section 2.2 in the text.)
- Universe is about 74% H, 24% He, 2% other elements
- Big Bang produced H, He, a bit of Li—all heavier elements formed in stars
- Stars form out of gas, create heavy elements, and return the elements to the gas when they die, so metallicity increases with each generation of star formation: good estimate of the age of a stellar population
- Population I stars are young and metal-rich ($Z \geq 0.01$), population II stars are relatively old and low in metals ($Z \leq 0.001$).
- Thin disk is Population I, halo is Population II, thick disk is intermediate.

• Globular clusters

  - Spherical clusters of old stars located in halo
  - At least 150
  - Ages range from 11 to a little over 13 Gyr old (age of universe 13.7 Gyr).

• Dark matter. About 95% of the mass of the Galaxy. More on that later.