ASTR368
The Milky Way
Chapter 24

The Milky Way

Summary: What is the Milky Way?
a. The band of light (stars) and dark patches (dust)
b. Our home Galaxy. It is a larger spiral galaxy and has around 200 billion stars. Bigger galaxies exist, but MW definitely on upper end

We are of course closer to the MW than any other galaxy, but we're stuck in the middle! That presents a problem.

Attempts to discern structure of MW

Herschel (late 1700s) /Kaptyn (late 1800s) both used star counts. Their method assumes that 1) all stars have approximately the same luminosity, 2) the number density of stars is roughly constant, and 3) we can see all the stars in the Galaxy. None of these asssumptions are true, but interstellar dust (reason #3) is the biggest impediment to the method.

Because dust was not accounted for, they found that the Universe that is only ~ 8 kpc large radially (~ 15 kpc in total), and ~ 1700 pc in and out of the plane (~ 3 kpc total). The Sun is 650 pc from the Galactic center. Oops.

Harlow Shapley noticed that globular clusters are not distributed uniformly, but instead are found preferentially toward the constellation of Sagittarius. He also found that most distant clusters are 70 kpc away - so Galaxy must be much larger than Kaptyne Universe. This model was too large! Due to bad calibration on the distances for globular clusters. Still, it was way better than the star count models.

Until the 1920s, we were still unsure about whether the universe consisted of just the Milky Way, or whether there were other galaxies. The "Great Debate," also called the "Shapley–Curtis Debate," was held on 26 April 1920 at the Smithsonian Museum of Natural History, between the astronomers Harlow Shapley and Heber Curtis. It concerned the nature of so-called spiral nebulae and the size of the universe. Shapley believed that these nebulae were relatively small and lay within the outskirts of the Milky Way galaxy, while Curtis held that they were in fact independent galaxies, implying that they were exceedingly large and distant.

To back up his claims, Shapley argued that if the spiral nebulae were external galaxies, this would challenge the accepted view of the universe. If Andromeda were not part of the Milky Way, then its distance must have been on the order of 10^8 light years - a span most contemporary astronomers would not accept. Shapley had also observed a nova in Andromeda (now thought to be a supernova) that had briefly outshone Andromeda itself, constituting a seemingly impossible output of energy were Andromeda in fact a separate galaxy. Finally, Adriaan van Maanen, a well-respected astronomer of the time, claimed he had observed the Pinwheel Galaxy rotating, implying that its orbital velocity would be enormous and there would be a violation of the universal speed limit, the speed of light.

Curtis, on the other hand, contended that Andromeda and other such as "nebulae" were separate galaxies, or "island universes" (a term invented by the 18th-century philosopher Immanuel Kant, who also believed that the "spiral nebulae" were extragalactic). He showed that there were more novae in Andromeda than in the Milky Way. From this, he could ask why there were more novae in one small section of the galaxy than the other sections of the galaxy, if Andromeda were not a separate galaxy but simply a nebula within Earth's galaxy. This led to supporting Andromeda as a separate galaxy with its own signature age and rate of nova occurrences.[citation needed] Curtis also noted the large radial velocities of spiral nebulae that suggested they could not be gravitationally bound to the Milky Way in a Kapteyn-model Universe. In addition, he cited dark lanes present in other galaxies similar to the dust clouds found in Earth's own galaxy, explaining the zone of avoidance. Curtis stated that if van Maanen's observation of the Pinwheel Galaxy rotating were correct, he himself would have been wrong about the scale of the universe and that the Milky Way would fully encompass it.

Later in the 1920s, Edwin Hubble showed that Andromeda was far outside the Milky Way by measuring Cepheid variable stars, proving that Curtis was correct. On other points, the results were mixed (the actual size of the Milky Way is in between the sizes proposed by Shapley and Curtis), or in favor of Shapley (the Sun was near the center of the galaxy in Curtis's model, while Shapley correctly placed the Sun in the outer regions of the galaxy). It later became apparent that van Maanen's observations were incorrect—one cannot actually see the Pinwheel Galaxy rotate during a human lifespan.

Basics of MW structure

Before we can start to describe the Milky Way in detail, we need to introduce a few important quantities.

Mass-to-light ratio

Tells us about the stars that are making the light. If, for example, there was lots of dark matter, the mass to light ratio would be large. By summing up all the masses and luminosities from the initial mass function, we find $M/L \sim 3\,M_\odot/\,L_\odot$ - it takes 3 solar masses on average to create one solar luminosity.

Derivation of "average" stellar mass

We know that there is a relationship between stellar luminosity and stellar mass: massive stars are much more luminous than low mass stars.

$$\frac{L}{L_\odot} = \left(\frac{M}{M_\odot}\right)^\alpha \tag{1}$$

You may have learned last semester that $\alpha = 3.5$. For more accuracy, $\alpha \simeq 4$ for $M > 0.5\ M_\odot$ and $\alpha \simeq 2.3$ for $M < 0.5\ M_\odot$ - 3.5 is a nice average value though.

Rearranging, and inserting the average M/L, $M/(3\ M_\odot) = L/\,L_\odot = (M/\,M_\odot)^\alpha$. So $1/3 = (M/\,M_\odot)^{\alpha-1}$ and $\langle M\rangle/\,M_\odot = (1/3)^{1/(\alpha-1)}$ which is 0.7 for $\alpha = 4$. Therefore, most light in the Galaxy comes from little stupid stars.

Scale Height

How can we define the size of various components? If the distribution decreases exponentially, $S = S_0 \exp(-z/H)$, where S is some quantity of interest, z is the distance, and H is a quantity called the "scale height," the distance over which the quantity decreases by a factor of e. Large scale heights are for more extended populations. Think about the differences we saw for the distribution of H I and CO.

For example, see the derivation for pressure in an atmosphere:

$$\frac{dP}{dz} = -g\rho \text{ (hydrostatic equilibrium)} \tag{2}$$

$$\overline{m}P = \rho kT \text{ (ideal gas law, with density and average mass per particle)} \tag{3}$$

so

$$\rho = \frac{\overline{m}P}{kT} \tag{4}$$

and therefore

$$\frac{dP}{dz} = -\frac{g\overline{m}P}{kT} = \frac{P}{H}\,, \tag{5}$$

where H is scale height $= kT/\overline{m}g$. Rearrange to get

$$\frac{dP}{P} = \frac{dz}{H} \tag{6}$$

We can then integrate to get

$$P = P_0 \exp(-z/H)\,. \tag{7}$$

This is only strictly applicable if the distribution decreases exponentially. If it doesn't, we can define a radius that contains half the light (the "half light radius"), or some other percentage.

Components of the Milky Way

1) Disk
2) Halo (incl. globular clusters and dark matter)
3) Bulge
4) BH at center

We can group Galaxies into Disk and Spheroidal components. We'll discuss each of these in turn.

Review: young stars: OBA, high metallicity, low mass to light, low B-V colors

Disk

About 50 kpc across (compare with 5 kpc for Kaptyne and 100 kpc for Shapley). Contains all gas/dust/young stars/spiral arms. Very thin - aspect ratio similar to DVD. In outer regions, warps considerably. Sun ~ 8.1 kpc from center of Galaxy, in disk midplane. Contains spiral structure

We can further divide the disk into "thin"/"thick" that fall off exponentially. Thin is $6 \times 10^{10}\ M_\odot$ stars and 0.5×10^{10} dust+gas. Thick is a few percent of this.

Overall stellar density:

$$n(z,R) = n_0(e^{-z/z_{\rm thin}} + 0.085e^{-z/z_{\rm thick}})e^{-R/h_R} \tag{8}$$

Within thin disk, we can even sub-divide into "young thin disk" and "old thin disk." Young thin disk scale height ~ 50 pc. Has neutral material, molecular material, OB clusters/H II regions/molecular clouds. Old thin disk scale height roughly 325 pc (G and K stars). Thick disk scale height ~ 1 kpc. Has stars, neutral material. Only $\sim 2\%$ the number density of the thin disk, at thin disk maximum (mid-plane). Maybe only 3% the mass of the thin disk.

The disk is where stars form.

Halo

Spheroidal; stellar and dark matter halos. Stellar Halo has form

$$n = n_0(r/a)^{-3.5} \tag{9}$$

Scale height 3kpc (big!).

Contains globular clusters.
These are groupings of 10^5 stars that orbit the center of mass of the Galaxy. ~ 200 in Galaxy
Old stars, ~ 10 billion years
Two classes, one confined to disk (younger) and one with more spherical distribution (older)

Dark matter halo has density distribution

$$\rho = \frac{\rho_0}{\frac{r}{a}\left(1+\frac{r}{a}\right)^2}\,, \tag{10}$$

with a, the "scale radius", $a = 2.8$ kpc as a good fit for the Milky Way (but it varies from galaxy to galaxy). This is known as the Navarro-Frenk-White (NFW) profile and is the most commonly used dark matter profile (but not the only one in use!).

When $r \ll a$, $\rho \propto 1/r$. When ra, $\rho \propto 1/r^3$. Disk falls off quicker, so percentage of DM increases with radius. Perhaps $5 \times 10^{11}\ M_\odot$ within 50kpc and $2 \times 10^{12}\ M_\odot$ within 230 kpc; 95% of the entire mass of MW.

What makes up dark matter? It seems most likely that it is some as-yet-undiscovered subatomic particle, such as weakly interacting massive particles (WIMPs) or axions. Another is massive compact halo objects (MACHOs), e.g. solitary black holes, neutron stars, burnt-out dwarfs, etc. We don't think there are enough MACHOs though. The other main possibility is that dark matter is composed of primordial black holes, black holes formed just after the big bang.

One option is weakly interacting massive particles (WIMPs).

Bulge

Contains old stars
~ 1 kpc in radius
Form

$$n = n_0 \exp(-((x/x_0)^2 + (y/y_0)^2 + (z/z_0)^2)^{0.5}) \tag{11}$$

(Dwek et al. '95), so $\propto e^{-x}$ in a given direction. An alternate form is

$$\log[I(r)/I_e] = -3.3307[(r/r_e)^{(1/4)} - 1] \tag{12}$$

Scale Height ~ 0.4 kpc.

BH at center (see below).

Galactic lobes parallel to Galactic plane.

Molecular CMZ

Bar (not really bulge or disk. . . .)

~ 4 kpc in radius Oriented about 45 deg. To our line of sight

Black Hole (Sgr A*)

From stellar orbits, we know it is $\sim 4 \times 10^6\ M_\odot$. Radio emission (synchrotron) is evidence of magnetic fields, and free electrons (ionized gas) X-ray emission is from the accretion disk that surrounds the black hole. From these observations we know that our black hole is not accreting much material presently. The observations of lobes extending out of the center of the Galaxy hints at past accretion events.

Let's take a while to look at table 24.1 Which component(s) are:
Most massive
Most luminous
Most metal rick/poor
Oldest/Youngest
Largest/smallest scale height

Questions: Yes, a in NFW profile is different for each galaxy. Why is thin disk so thin? Angular momentum! The spinning galaxy naturally leads to a thin disk. Better question is why is thick disk thicker? Answers vary from heating of thin disk, high velocity stars have time to migrate from thin to thick, mergers, formation processes, even interactions with other galaxies.

MW Kinematics (24.3)

Before we can talk about kinematics, we have to discuss the Galactic coordinate system, which has Galactic latitude $b = 0$ in the midplane, positive toward the north Galactic pole and Galactic latitude $\ell = 0$ toward the Galactic center, increasing eastward. Think of this as being inside a celestial sphere, then longitude and latitude are as they are on Earth with the midplane being along the equator. Galactic coordinates are therefore centered on the Sun.

Most of astronomy is done in what is called the celestial coordinate system with right ascention (RA) and declination (dec). We won't go into those here, but ask me after class if you are interested, and take Observational Astronomy ASTR469. Converting between the two requires some spherical trig.

Let's define yet another system!!! Everything in the Galaxy rotates about the Galactic center. We therefore need a coordinate system centered on the Galactic center, because the Sun itself is constantly in motion. Much of understanding the kinematics of the Milky Way concerns establishing a stable, unmoving "platform" by removing the Sun's motion. The Sun is moving not just around the Galactic center, but up out of the plane and away from the Galactic center as well. [Note that all this assumes that the Earth's motion around the Sun is subtracted from observed velocities.] We can therefore define:

$$\Pi = dR/dt \tag{13}$$
$$\Theta = Rd\theta/dt \tag{14}$$
$$Z = dz/dt \tag{15}$$

where R is from the Galactic center to the Sun, θ is from the Galactic center to the Sun clockwise (in the direction of rotation), and z is toward the north Galactic pole. But this only solves part of the problem since our observations are still from the Earth-Sun system.

Local Standard of Rest

Let's keep working on defining that stable platform. We can remove the Sun's motion by determining the average motion near the Sun. This is known as the "local standard of rest" (LSR). We can define a "dynamical LSR" based on a point located at the Sun moving in perfectly circular motion, and the "kinematic LSR" based on the average motions of stars near the Sun. We will use the dynamical LSR here.

So, the LSR must have:

$$\Pi_{LSR} = 0 \tag{16}$$
$$\Theta_{LSR} = \Theta_0 \tag{17}$$
$$Z_{LSR} = 0 \tag{18}$$

where $\Theta_0 = \Theta(R_0)$ and R_0 is the distance from the Galactic center to the Sun. Observations have shown that $\Theta_0 = -235\ \mathrm{km\,s^{-1}}$ and $R_0 = 8.2$ kpc ($\Theta_0 = 220\ \mathrm{km\,s^{-1}}$ is the accepted value; $R_0 = 8.5$ kpc is the accepted value, but recent results have shown that these need to be updated).

Now we have our stable platform! We can define motion with respect to the LSR, and this is called the "peculiar velocity" and uses u, v, and w:

$$u = \Pi - \Pi_{LSR} = \Pi \tag{19}$$
$$v = \Theta - \Theta_{LSR} = \Theta - \Theta_0 \tag{20}$$
$$w = Z - Z_{LSR} = Z \tag{21}$$

and stars have measured peculiar velocities of

$$\Delta u = u - u_\odot \tag{22}$$
$$\Delta v = v - v_\odot \tag{23}$$
$$\Delta w = w - w_\odot \tag{24}$$

What we really want is to know the Solar parameters so we can correct for them. We can do this by observing lots of stars locally, or in principle gas clouds:

$$u_\odot = -\langle u \rangle \tag{25}$$
$$v_\odot = -\langle v \rangle - \langle \Delta v \rangle \tag{26}$$
$$w_\odot = -\langle \Delta w \rangle \tag{27}$$

Observations of average stellar motions have shown that:

$$u_\odot = -10.0 \pm 0.4 \text{ km s}^{-1} \tag{28}$$
$$v_\odot = 5.2 \pm 0.6 \text{ km s}^{-1} \tag{29}$$
$$w_\odot = 7.2 \pm 0.4 \text{ km s}^{-1} \tag{30}$$

We can then remove the Sun's motion from our observations.

If we define the geometry we see that $v_r = \Theta \cos\alpha - \Theta_0 \sin\ell$ [generally the quantity measured. How measured?] $v_t = \Theta \sin\alpha - \Theta_0 \cos\ell$.

So that we don't have to deal with α we can define the angular velocity curve as $\Omega(R) = \Theta(R)/R$

and after some algebra

$$v_r = (\Omega - \Omega_0) R_0 \sin\ell \tag{31}$$
$$v_t = (\Omega - \Omega_0) R_0 \cos\ell - \Omega d \tag{32}$$

where d is the distance. We see that we now have a model for velocities based on Galactic rotation! This assumes circular motion.

Jan Oort, famous Dutch astronomer found that if we assume that Ω is smoothly varying, we can Taylor expand it and again after some algebra

$$v_r \simeq \left[\frac{d\Theta}{dR}\Big| R_0 - \frac{\Theta_0}{R_0} \right] (R - R_0) \sin\ell \tag{33}$$
$$v_t \simeq \left[\frac{d\Theta}{dR}\Big| R_0 - \frac{\Theta_0}{R_0} \right] (R - R_0) \cos\ell - \Omega_0 d \tag{34}$$

$$A = -\frac{1}{2} \left[\frac{d\Theta}{dR}\Big| R_0 - \frac{\Theta_0}{R_0} \right] \tag{35}$$
$$B = -\frac{1}{2} \left[\frac{d\Theta}{dR}\Big| R_0 + \frac{\Theta_0}{R_0} \right] \tag{36}$$

So therefore

$$v_r \simeq Ad \sin 2\ell \tag{37}$$

$$v_t \simeq Ad \cos 2\ell + Bd \tag{38}$$

What are A and B? They don't have clean meanings, but

$$\Omega_0 = A - B \tag{39}$$

$$d\Theta/dR|R_0 = -(A+B) \tag{40}$$

Properties of Galactic rotation Q: At what distance will the radial velocity be a maximum?
A: At distance tangent to line of sight, which is the minimum distance:
$R_{\text{min}} = R_0 \sin \ell$ which gives

$$v_{\text{r,max}} = \Theta(R_{\text{min}}) - \Theta_0(R_0) \sin \ell \tag{41}$$

and if we Taylor expand $\Theta(R_{\text{min}})$ about R_0, we get

$$v_{\text{r,max}} \simeq 2AR_0(1 - \sin \ell) \tag{42}$$