Astronomy 400B Lecture 4: The Milky Way

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Today's class will regard the Milky Way!

1 Solar Neighborhood

Stars in the local neighborhood provide a lot of our information about the Milky Way and, frankly, a lot of what we infer about any galaxy. Learning about the stars requires knowing something about their intrinsic luminosities and masses. This requirement results in the need to have robust distance estimates for a large number of stars.

1.1 Parallax

Trignometric parallax provides a direct distance estimate for very nearby stars. Trignometric parallax is the shift in the angular position on the sky of a star as viewed from different locations of the Earth's orbit around the Sun.

For an object at distance d, the parallax p is

$$\frac{1 \text{ AU}}{d} = \tan p \approx p \tag{1}$$

The pc is the distance where the parallax of a star would be $p = 1$ arcsec. The closest star is Proxima Centuari, with $p = 0.8$ arcsec and a $d = 1.3$ pc.

1.2 Distance Modulus

For nearby (Galactic) objects, we can relate the difference between the apparent and absolute magnitude of an object with its distance or parallax through the *distance modulus* equation

$$m - M = 5 \log \left(\frac{d}{10 \text{ pc}} \right) = 5 \log \left(\frac{0.1 \text{ arcsec}}{p} \right). \tag{2}$$

1.3 Luminosity and Mass Functions

The luminosity and mass functions of stars enable us to learn about the star formation history of the Galaxy and about the star formation process itself.

See Figure 2.3 of Sparke and Gallagher

The luminosity and mass functions reflect combinations of the numbers of stars per unit mass and the mass to light ratio of stars as a function of mass.

The luminosity function is

$$\Phi(x) = \frac{\text{number of stars per unit magnitude}}{\text{detectable volume}} \tag{3}$$

1.3.1 Initial Luminosity Function

Stars have a finite lifetime, so the observed luminosity function defined above is a time-evolved distribution where some fraction of stars have left the main sequence after their MS lifetime τ_{MS}. If the star formation rate of the disk has been roughly constant, the initial luminosity function is related to the observed luminosity function as

$$
\begin{aligned}
\Psi(M_V) &= \Phi_{\mathrm{MS}}(M_V) \ \text{ for } \tau_{\mathrm{MS}}(M_V) \geq \tau_{\mathrm{gal}} \\
&= \Phi_{\mathrm{MS}}(M_V) \times \frac{\tau_{\mathrm{gal}}}{\tau_{\mathrm{MS}}(M_V)} \ \text{ when } \tau_{\mathrm{MS}}(M_V) < \tau_{\mathrm{gal}}
\end{aligned}
\tag{4}
$$

where $\tau_{\mathrm{gal}} \approx 8 - 10$ Gyr is the star formation timescale of the disk.

1.3.2 Initial Mass Function

The stellar initial mass function, or IMF for short, is one of the most important distributions in astronomy and represents an interesting combination of physics in molecular gas, cooling, and gravity. The IMF represents the initial number of stars per unit mass that forms in a typical volume. We write

$$
\xi(M)dM = \xi_0 (M/M_\odot)^{-2.35} \frac{dM}{M_\odot}
\tag{5}
$$

The power-law slope -2.35 is called the *Salpeter* slope.

See Figure 2.5 of Sparke and Gallagher

2 Stars in the Galaxy

Understanding the structure of the Galaxy is tightly connected to understanding the distances to stars at all distances.

2.1 Distances from Motions

The tangential and radial velocities of stars can inform us about their distances. The radial (line-of-sight) velocities can be measured via the Doppler shift we discussed previously. The tangential velocity is related to the apparent proper motion μ on the sky of an object and its distance d. If the relation between tangential and radial velocities is known, then by measuring the radial velocity and proper motion we can find an object's distance.

The tangential velocity is

$$
v_t = \mu \ (\text{radians/time}) \times d, \ or \ \mu \ (0.001 \text{arcsec/yr}) = \frac{v_t \ (\text{km s}^{-1})}{4.74 \times d \ (\text{kpc})}
\tag{6}
$$

We can identify stars that orbit the supermassive black hole at the center of the Galaxy. The orbits of these stars allow us to measure the mass of the Galactic SMBH, and since we can compute their physical tangential velocity their distances can be inferred. It turns out we are $d = 8.46 \pm 0.4$ kpc away from the Galactic center.

2.2 Spectroscopic and Photometric Parallax, and Galactic Structure

The shapes and depths of spectral lines of stars depend on properties that correlate with their mass and luminosity. Given a measurement of the stellar flux, the absolute distances to stars can be estimated from their spectra. We call this technique the *spectroscopic parallax*. Similarly, based on the color of star one may infer a temperature and then use other information to classify the star as a dwarf or giant and constrain the mass, intrinsic luminosity, and distance. This method, called the *photometric parallax*, is less reliable but still widely employed.

Much of what we know about the structure of the stellar disk of the Milky Way is inferred using these methods. The proper motions of many stars in the Milky Way are too small to be reliably measured, so

the only distance estimates that we have come from either spectra or photometry. Obviously, photometry is available for many, many more stars!

The shape of the stellar disk can be expressed in terms of the radius R, vertical height z, and spectral type S as

$$n(R, z, S) = n(0, 0, S) \exp\left[-R/h_R(S)\right] \exp\left[-|z|/h_z(S)\right]. \tag{7}$$

Here, h_R is the disk scale length and h_z is the scale height. Sensibly, the scale length and height do depend strongly on the stellar type. The scale height of older and lower mass stars is larger (~ 350 pc) than for young and massive stars (~ 200 pc. HI and molecular gas have even smaller scale heights.

See Figure 2.8 of Sparke and Gallagher. See Table 2.1 of Sparke and Gallagher.

2.3 Star Formation Rate of the Milky Way

We can use the stellar luminosity of the disk and a typical mass to light ratio to infer the disk stellar mass. For $L_{\text{disk}} \sim 1.5 \times 10^{10} L_\odot$ and $M/L \sim 2$ for the most abundant stars, we find a stellar mass of $M_\star \sim 3 \times 10^{10} M_\odot$. The disk is about ~ 10 Gyr old, and stars loose about half their mass in winds over this time when averaged over the typical IMF. That means the star formation rate in the disk is $\sim (3-5)~M_\odot~\text{yr}^{-1}$. The cold gas in the Milky Way disk can sustain this star formation rate for only a few gigayears.

2.4 Velocity Dispersion

The non-zero height of the disk implies that there has to be kinematical support of disk stars relative to the disk gravitational potential. The vertical velocity dispersion is

$$\sigma_z^2 \equiv \left\langle v_z^2 - \langle v_z \rangle^2 \right\rangle. \tag{8}$$

The velocity dispersion of stars tends to increase with their age (in conjunction with their scale height). This fattening of the disk results from scattering processes that arise from the non-uniformity of the disk. There are velocity dispersions in the other polar directions as well, typically with $\sigma_R \geq \sigma_\phi \geq \sigma_z$.

We can also estimate the *asymmetric drift* of a star, which reflects the orbital velocity lag of the star relative to a circular orbit at the Sun's position. This property will be discussed more later.

3 Stellar Clusters

Stars in galaxies typically form in *clusters*, collections of stars that are gravitationally bound or structurally associated (loosely bound). Stars in a cluster are roughly co-eval, so there is a lot we can learn from them!

The Hertzsprung-Russell diagram of the clusters reflect an *isochrone*, a line corresponding to a single age stellar population. The location of the *main sequence turn-off* indicates the age of the stellar population.

See Figure 2.12 of Sparke and Gallagher.

3.1 Open Clusters

There are > 1000 collections of (usually) recently-formed stars called *open clusters* consisting of stars with ages $\lesssim 1$ Gyr, total luminosities of $L \sim 100 - 10,000 L_\odot$, and several hundred total stars.

See Table 2.2 of Sparke and Gallagher.

3.2 Globular Clusters

There are much denser, more massive, and typically older collections of stars called *globular clusters*. Globulars may have luminosities of $10^5 - 10^6~\sim L_\odot$ and $10^5 - 10^6$ stars. Most of the globulars are more than $10 \sim$ Gyr old and very metal poor.

See Table 2.3 of Sparke and Gallagher.
See Figure 2.14 of Sparke and Gallagher.

4 Galactic Rotation

The disk of the Milky Way rotates, and it rotates *differentially* such that the stars in the inner parts of the galaxy orbit the center of the galaxy more rapidly than stars in the outer disk do. Differential rotation by looking at the proper motions of disk stars, and seeing that inner stars were passing us while outer stars were trailing. For stars near the Sun, proper motions showed a $\cos(2l)$ dependence on Galactic longitude that can be understood via a differentially rotating disk.

4.1 Local Standard of Rest

The sun lies about 15pc out of the disk plane, and the orbit of the Sun about the GC is not purely circular. We define the *local standard of rest* by the average motions of stars near the Sun correcting for asymmetric drift. Relative to the standard, the Sun is moving toward the GC, leading the rotation, and moving up relative to the disk plane.

In 1985, the IAU adopted a LSR radius of $R_0 = 8.5$ kpc from the GC and $V_0 = 220$ km s^{-1} for its circular velocity. Current estimates are closer to $R_0 \sim 8$ kpc and $V_0 \sim 200$.

4.2 Measuring Galactic Rotation

For disk stars, we can determine their radial velocity relative to the Sun assuming circular orbits.

See Figure 2.19 of Sparke and Gallagher.

The Sun is at R_0, V_0, while the star has a radius R and orbital speed $V(R)$. The radial velocity relative to the Sun is

$$V_r = V \cos \alpha - V_0 \sin l. \tag{9}$$

But $\sin l/R - \sin(\alpha + \pi/2)/R_0$, so

$$V_r = R_0 \sin l \left(\frac{V}{R} - \frac{V_0}{R_0} \right). \tag{10}$$

For solid body rotation, $V(R) = constant$ and the relative radial velocity would be zero. Instead, V/R decreases with R.

See Figure 2.20 of Sparke and Gallagher

As a function of Galactic longitude, we have

- For $0 < l < 90$, V_r is positive for nearby objects, and negative for distant objects on the other side of the Galaxy with $R > R_0$.

- For $90 < l < 180$, V_r is always negative.

- For $180 < l < 270$, V_r is always positive.

- For $270 < l < 360$, the first quadrant pattern is repeated with opposite sign.

4.3 Oort Constants

When an object is near the Sun, $R \approx R_0 - d \cos l$ and we can approximate the radial velocity as

$$V_r \approx d \sin(2l) A \tag{11}$$

where

$$A \equiv \left[-\frac{R}{2} \frac{dV}{dR} \right]_{R_0} \tag{12}$$

is called the *Oort* constant after Jan Oort. The A constant measures the local shearing motions in the disk. For the Milky Way, $A = 14.8 \pm 0.8$ km s^{-1} kpc^{-1}.

The tangential velocity of a star relative to the Sun is

$$V_t = V \sin \alpha - V_0 \cos l \tag{13}$$

But $R_0 \cos l = R \sin \alpha + d$, and we have

$$V_t = R_0 \cos l \left(\frac{V}{R} - \frac{V_0}{R_0} \right) - V \frac{d}{R} \tag{14}$$

Near the Sun, $R_0 - R \approx d \cos l$, so

$$V_t \approx d[A \cos(2l) + B] \tag{15}$$

where

$$B = -\frac{1}{2} \left[\frac{1}{R} \frac{d(RV)}{dR} \right] \tag{16}$$

where B is the second Oort constant that measures vorticity. $B = -12.4 \pm 0.6$ km s^{-1} kpc^{-1} in the Solar neighborhood.

4.4 Tangent Point Method

In the inner Galaxy $R < R_0$, the *tangent point method* can be used to find the rotation curve. Since V/R decreases with radius, if we look at regions near the Galactic center in projection ($0 < l < 90$), then the radial speed $V_r(l, R)$ is maximized at the tangent point where the line of sight is closest to the GC. There, we have

$$R = R_0 \sin l \tag{17}$$

and

$$V(R) = V_r + V_0 \sin l \tag{18}$$

The galactic rotation curve can then be inferred from the maximum velocity in Figure 2.20 at each l.
See Figure 2.20 of Sparke and Gallagher

4.5 Outer Galaxy

Measuring the rotation of the outer galaxy is done by determining distances via spectroscopic or photometric parallax, and then measuring V_r via emission lines. We think $V(R)$ is either flat or increasing in the outer galaxy.

5 Dark Matter

For a spherical mass distribution, the velocity of a circular orbit related to the interior mass by

$$V^2 = \frac{GM(<R)}{R} \tag{19}$$

If the circular velocity is flat in the outer galaxy, we would infer that

$$M(<R) \propto R \tag{20}$$

Clearly, the exponential disk cannot supply this mass growth with radius. But we know how to relate $M(<R)$ to a density profile through the integral

$$M(<R) = 4\pi \int_0^R \rho(r) r^2 dr \tag{21}$$

Further if we assume $\rho(r) \propto r^\alpha$, then

$$M(<R) \propto R \propto R^{3+\alpha} \tag{22}$$

So we infer that a spherical density profile would be declining at $\rho(r) \propto r^{-2}$ in the regime where the mass was growing linearly and the circular velocity is flat.

That mass grows with radius implies there is a *lot* of mass in the exterior of the galaxy.

6 The Gaseous Disk

The distribution of gas in the galaxy can be determined by measuring the line of sight velocity of emission lines and then assuming the gas is on a circular orbit. We call this approach determining the *kinematical distance* to the gas. This method can be used on both HI and H_2 (well, CO) to determine the relative distribution of neutral and molecular gas in the Galaxy.

See Figure 2.22 of Sparke and Gallagher

The MW has about $6 \times 10^9 M_\odot$ of HI and about $3 \times 10^9 M_\odot$ of H_2. The molecular hydrogen is mostly in the solar circle, but the HI extends much further. The molecular disk is about 80pc thick near the Sun, while the HI is about twice as extended.

There is some HI gas outside of the midplane, and much of that is moving toward us. There are HI gas clouds called *high velocity clouds* because they are moving at ~ 100km s^{-1} toward us. We don't know what causes HVCs.

See Figure 2.22 of Sparke and Gallagher

Gas above ~ 1kpc is mostly warm or hot ionized media. This gas absorbs CIV, and the hotter gas emits OVI.

In the inner 3kpc of the galaxy, interior to a molecular ring, the surface density of galaxy drops again. In the inner 200pc of the Galactic Bulge is a gas rich region with about one hundred million solar masses of gas.

The interstellar medium is comprised of a variety of phases that are mixed on scales below ~ 1kpc:

- There are a few thousand gian molecular clouds with about 20pc sizes, $M > 10^5 M_\odot$, and $n \sim 200 - 10^4$ cm^{-3}.

- The GMCs are surrounded by neutral hydrogen with $n \sim 25$ and $T < 80$K. Near the sun HI can have $T \sim 8000$K and $n \sim 0.3$cm^{-3}.

- Hot diffuse plasmas with $n \sim 0.002$cm^{-3} and $T \sim 10^6$K surrounds the HI.

- Around hot stars HII regions can form, with photodissociation regions located at the boundary with surrounding dense gas.

See Table 2.4 of Sparke and Gallagher

GMCs are turbulent, and have supersonic line widths.

6.1 Dust

There is a lot of dust in Milky Way gas and in the gas of many other galaxies. The dust absorbs about half the optical and UV light of the galaxy. There is about one dust grain per trillion hydrogen atoms, and the grains are typically $\lesssim 0.3$ microns in size. About $10 - 20\%$ of the dust is in small polycyclic aromatic hydrocarbons (PAH) that absorbs light and emits photoelectrons, which thermalize and heat the gas (forming the prime heat source for atomic HI). Hot dust is at $\sim 100K$ and emits at 30 microns, while cold dust is at 30K and emits at 100 microns.

See Figure 2.24 of Sparke and Gallagher

7 Recombination and the Ionization State of the ISM

Ionized hydrogen (proton plus electron) can undergo a recombination to form neutral hydrogen. The rate of this process depends on the properties of the ionized gas. We can write the recombination rate dn_e/dt that changes the number density n_e of free electrons as

$$\frac{dn_e}{dt} = n_e^2 \alpha(T_e) \tag{23}$$

where T_e is the temperature of the gas and $\alpha(T_e)$ is the "recombination coefficient"

$$\alpha(T_e) \approx 2 \times 10^{-13} \left(\frac{T_e}{10^4 \text{ K}} \right)^{-3/4} \text{ cm}^3 \text{ s}^{-1}. \tag{24}$$

There's a lot hidden in the coefficient!

We can also define the recombination time t_{rec} that characterizes the timescale over which the ionized gas will significantly increase its neutrality. The recombination time is given by

$$t_{rec} = \frac{n_e}{|dn_e/dt|} = \frac{1}{n_e \alpha(T_e)} \approx 1500 \text{ yr} \times \left(\frac{T_e}{10^4 K}\right)^{3/4} \left(\frac{100 \text{ cm}^{-3}}{n_e}\right) \tag{25}$$

In HII regions, t_{rec} is a few thousand years. In the diffuse ionized ISM, the recombination time is a few million years.

7.1 Cooling Rate and Time

Gas has an internal thermal energy of $E \propto nT$. If the gas radiates this thermal energy with an energy L, the cooling timescale for the gas is $t_{cool} \propto nT/L$. For optically thin gas, we can write

$$L = n^2 \Lambda(T) \tag{26}$$

and

$$t_{cool} \propto T/[n\Lambda(T)]. \tag{27}$$

The quantity $\Lambda(T)$ is called the "cooling function" and depends only on temperature.

See Table 2.5 and Figure 2.25 of Sparke and Gallagher.

At high temperatures $T > 10^7$ K, free-free cooling dominates such that $\Lambda(T) \propto T^{1/2}$ and $t_{cool} \propto \sqrt{T}/n$.

8 Jeans Mass

Since gas can cool, eventually the thermal random motions of the gas will be unable to support it against its own self-gravity. The condition for this self-gravitational collapse is called the Jeans criterion. A gas cloud of density ρ and temperature T will collapse if its diameter is

$$\lambda_J = c_s \sqrt{\frac{\pi}{G\rho}} \tag{28}$$

where c_s is the sound speed of the gas. We can express the sound speed in terms of the temperature and mean molecular weight of the gas

$$c_s^2 = k_\mathrm{B} T/\mu m_H \tag{29}$$

where m_H is the mass of the hydrogen atom. The mass within the Jeans diameter

$$M_J \equiv \frac{\pi}{6} \lambda_J^3 \rho = \left(\frac{1}{\mu m_H}\right)^2 \left(\frac{k_\mathrm{B} T}{G}\right)^{3/2} \left(\frac{4\pi n}{3}\right)^{-1/2} \frac{\pi^3}{3\sqrt{3}} \tag{30}$$

$$M_j \approx 20 \left(\frac{T}{10\mathrm{K}}\right)^{3/2} \left(\frac{100 \text{ cm}^{-3}}{n}\right)^{1/2} M_\odot. \tag{31}$$

If the cloud does collapse, it does so on the free fall time

$$t_{ff} = \sqrt{\frac{1}{G\rho}} \approx \frac{10^8}{\sqrt{n_H}} \text{ yr.} \tag{32}$$

If the cooling time is much less than the free fall time, the gas cloud will fragment in to smaller clouds during the collapse. Something must moderate this process because the star formation rate you would infer from converting the molecular gas into stars on a free fall time is many times larger than the observed star formation rate.