# 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

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

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

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

### 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 $\tau_{\rm MS}$. If the star formation rate of the disk has been roughly constant, the initial luminosity function is related to the observed luminosity function as

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

where $\tau_{\rm gal} \approx 8 - 10$ 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 $\mu$ 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

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

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 ($\sim$ 350 pc) than for young and massive stars ($\sim$ 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 $L_{\mathrm{disk}} \sim 1.5 \times 10^{10} L_{\odot}$ 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 $\sim$ 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 $\sim (3-5)\ M_{\odot}\ \mathrm{yr}^{-1}$. 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.**