The Milky Way

The Shape of the Galaxy
Stellar Populations and Motions
Stars as a Gas

March 19, 2024

University of Rochester

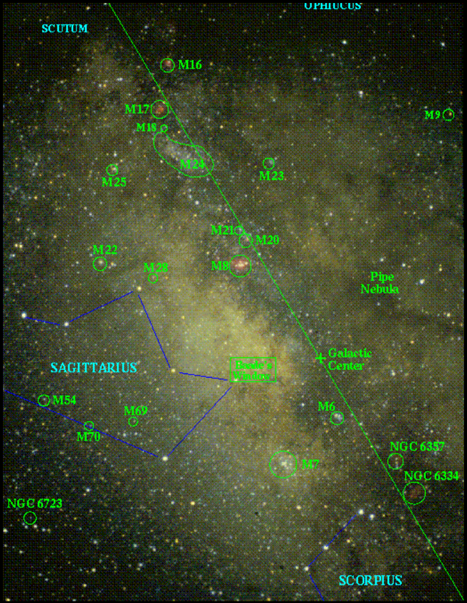
The Milky Way

Today's lecture:

- The shape of the Galaxy
- Stellar populations and motions
- Stars as a gas: Scale height, velocities, and the mass per unit area of the disk

Reading: Kutner Sec. 16.4, Ryden Sec. 19.1–19.3, Shu Ch. 12

Wide-angle photo and overlay key of the Sagittarius region of the Milky Way (from Bill Keel, U. Alabama).



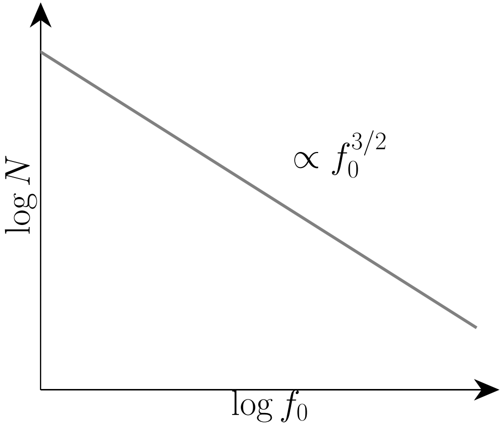
The number of stars brighter than f_0

Suppose stars are *uniformly distributed in space* with number density n and typical luminosity L. How many are brighter (i.e., have greater flux) than some value f_0?

Presuming there is no extinction, there is a distance r_0 corresponding to the flux f_0:

$$f_0 = \frac{L}{4\pi r_0^2} \quad \rightarrow \quad r_0 = \sqrt{\frac{L}{4\pi f_0}}$$

$$\implies N(f > f_0) = \frac{4\pi}{3} r_0^3 n = \frac{4\pi n}{3}\left(\frac{L}{4\pi f_0}\right)^{3/2} \propto f_0^{-3/2}$$



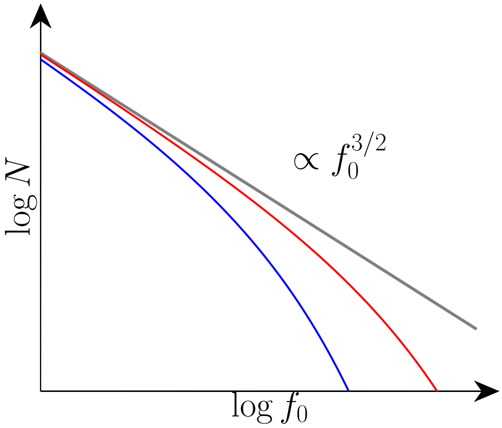
Shape of the Milky Way

Herschel (1785) and Kapteyn (1922) used this idea to characterize the shape of the Milky Way.

- If the MW has edges, N must decrease faster than $f_0^{-3/2}$ past the edges.
- Actual star counts at large fluxes are less than predicted by the $N \propto f_0^{-3/2}$ relationship.
- Implication: the MW has a finite size with identifiable edges.

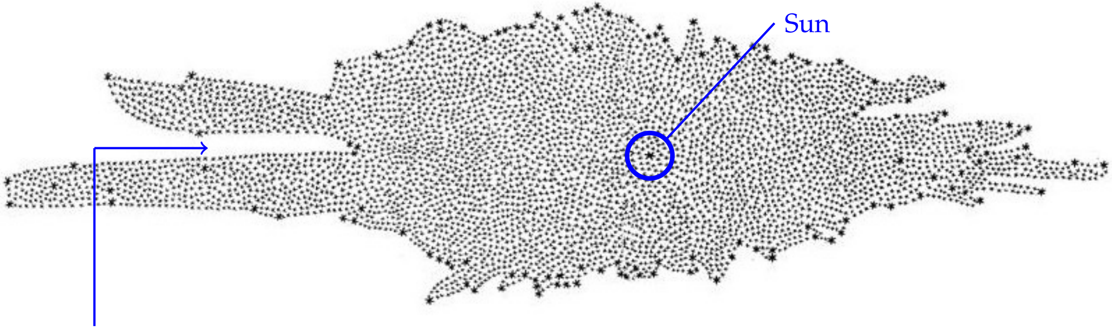
Red: star count in direction of Galactic disk
Blue: star count $\perp$ to Galactic disk

Observed counts:



Herschel's Milky Way (1785)

"Section of our sidereal system" (Herschel 1785). The long axis of the figure runs from $20^h22^m, +35°$ in Cygnus (left) to $8^h20^m, -35°$ in Puppis (right). The short axis points towards $12^h24^m, +58°$ in Ursa Major.



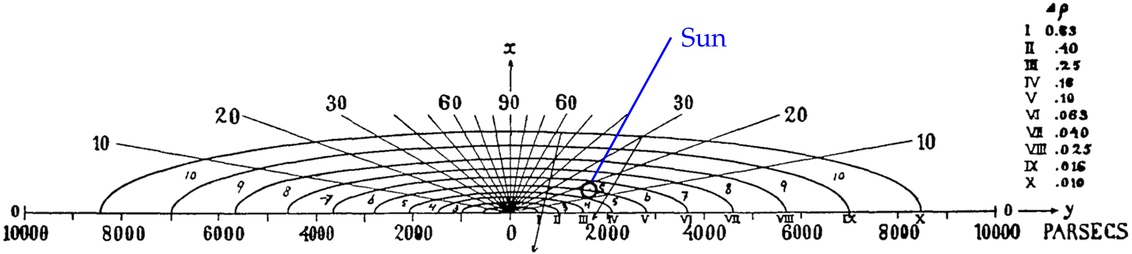
The Great Rift in the summer Milky Way, interpreted as a dearth of stars, is visible on the left. Herschel referred to this as "an opening in the heavens."

The Great Rift

The Great Rift (or Dark Rift) created by dust clouds between Cygnus and Sagittarius (Fujii 2012).

Kapteyn's "Universe" (1922)

By 1922, Kapteyn knew the distances to many nearby stars from parallaxes and proper motions and could calibrate the star counts in terms of stellar density n and a shape of the stellar assemblage in terms of hydrostatic structure (Kapteyn 1922).

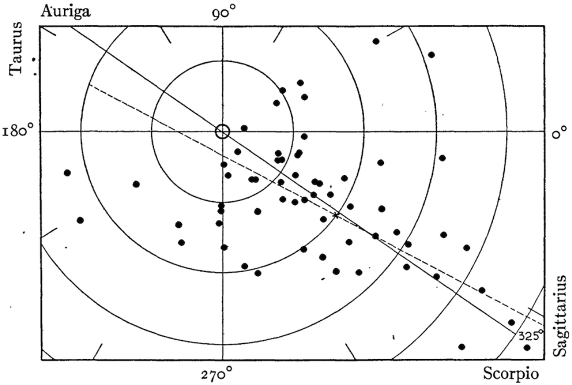


This enabled him to estimate a position for the Sun based on stellar density in the solar neighborhood: $r = 650$ pc, $z = 38$ pc. His MW model was a flattened ellipsoid $\sim$ 15 kpc wide and $\sim$ 3 kpc thick.

Galactocentric distance

Harlow Shapley (1919): globular clusters are massive and indicate Galactic structure better than stars due to lower scatter (Shapley 1919).

- Used Henrietta Leavitt's discovery of the Cepheid period-luminosity relation on RR Lyrae stars to measure distances.
- Solar distance from the center of the cluster distribution is 100 kpc (Shapley 1918).
- **Question**: What is the current estimate of our galactocentric position?



Globular cluster analysis by Shapley (1919). Dots are positions of globular clusters projected onto the plane of the MW. Circles are galactocentric radii in intervals of 10 kpc.

The Milky Way "Island Universe"

As you know, all these methods got the shape of the Galaxy and the Sun's distance from the center **quite wrong**. Why?

- Interstellar extinction is substantial in the Galactic plane and obscures most of the distant starlight.
- Both Herschel and Kapteyn were seeing only to the edge of the extinction, not to the edge of the stars.
- By Kapteyn's time, many astronomers were on the right track by analogy: the Milky Way is like the **spiral nebulae**, and we live well off-center, as Shapley found.
- Modern measurements of parallax of water-vapor masers in molecular clouds near the GC, and of the black hole at the Galactic center, give 8.15 ± 0.15 kpc for our Galactocentric radius (Reid et al. 2019).

Milky Way structure: Halo, bulge, and disk

- The globular clusters seem to trace out a spherical **halo** around the Galaxy, in which we are immersed.
- Non-cluster stars can be seen in the halo if you look carefully enough.
- Once we know where to look for the Galactic center, we notice other features: a **bulge** and a **disk**.

The Milky Way seen from Cerro Paranal (Bruno Gilli/ESO).

Halo, bulge, and disk

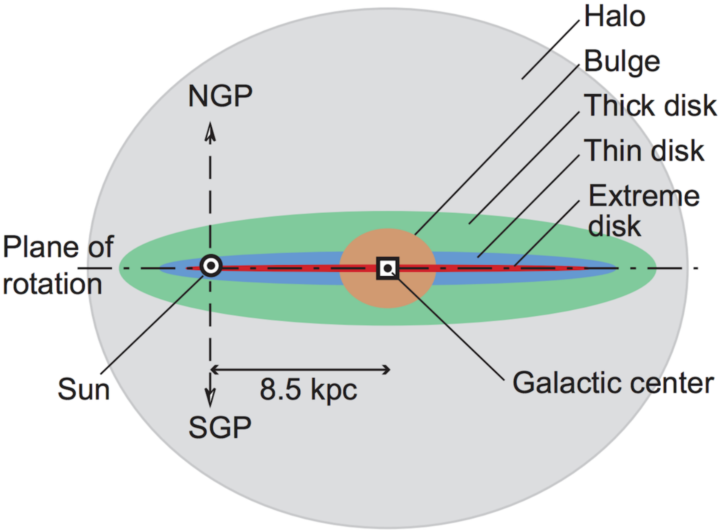
- **Bulge**: thick and bright concentration of stars surrounding the Galactic Center.
- **Disk**: a belt of stars and extinction passing through the center (this is the "Milky Way" proper).
- Since the belt seems not to have ends, we are also immersed in it.
- The distribution of stars is thicker than that of dust everywhere along the belt: there is a **thick disk** and a **thin disk** (much like other galaxies).

IR image of the Milky Way from the 2MASS All-Sky Survey.

Halo, bulge, and disk of NGC 891

IR mosaic of edge-on spiral galaxy NGC 891 from 2MASS (Kopan 2017).

Schematic structure of the Milky Way



The different components of the Galaxy (Buser 2000).

Mass of the halo, bulge, and disk

The different components of the Milky Way owe their distributions to differences in motion.

- The **disk** is dominated by rotation. Objects which belong to the disk have both random and rotational components to their motion, but the rotational component dominates.
- The **bulge** and **halo** are dominated by random motion with little or no evidence of rotation.

The dynamics and composition of stars are correlated:

Population I: Small dispersion of velocities — i.e., small random velocities — with absorption lines of heavy metals. Confined to a very thin plane. Relatively young. Example: the Sun.

Population II: Large dispersion of velocities, lying further from the Galactic Plane, and low metal content. Examples: globular clusters and halo stars.

- Population I lies predominantly in the disk, less in the bulge, and not in the halo. Population II are found in all three components.

Composition of the halo, bulge, and disk

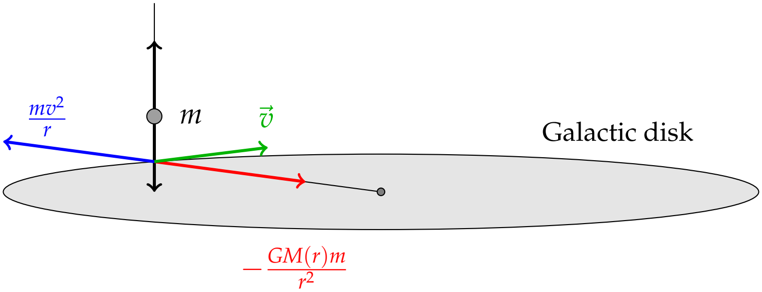
What is the Galaxy's mass? Stars move in response to the gravitational potential of the rest of the galaxy, so we can use their motion to trace out the mass distribution.

- The **systematic motions** (rotation) can be used with Newton's Laws to measure masses within the Galaxy.
- Note: This works even better with interstellar gas than with stars.
- The *visible* mass of the Galactic halo is small compared to that of the disk and bulge, but we have strong evidence that the true mass of the halo is similar to the other components and is dominated by **dark matter**.

Stars are too massive to be influenced by the pressure of the ISM but they collide inelastically very rarely, so their **random motions** can be used with **thermodynamics** to measure masses within the Galaxy. In this sense, stars can be thought of as particles in a gas or fluid.

M/A of the Disk in the Solar neighborhood

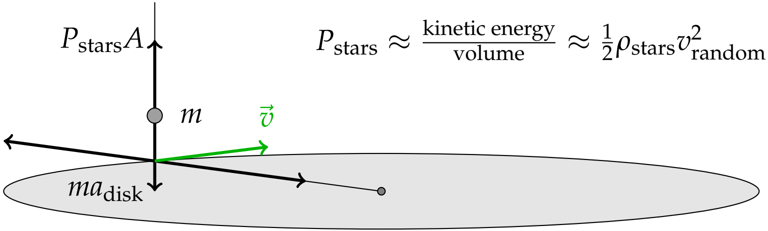
- The radial structure of the disk is determined in the usual manner from centrifugal support: balancing the force on a test particle at radius r from the mass $M(r)$ contained in interior orbits with centripetal acceleration.
- **Note**: This is just like a protoplanetary disk, or any other astro-disk.



M/A of the Disk in the Solar neighborhood

The vertical structure is determined by hydrostatic equilibrium, but there are two main differences from protoplanetary disks:

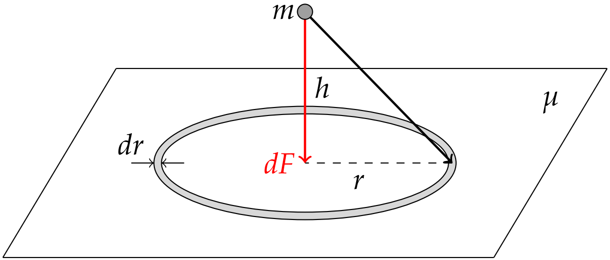
1. Much of a galactic disk is self-gravitating; the weight is from the disk itself, not from a "star" in the center.
2. The "pressure" is produced by the stars' motions.



$$P_{\text{stars}} \approx \frac{\text{kinetic energy}}{\text{volume}} \approx \frac{1}{2}\rho_{\text{stars}} v^2_{\text{random}}$$

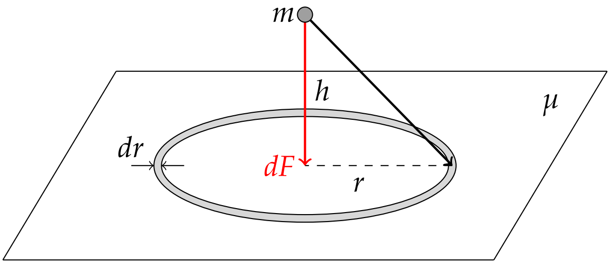
M/A of the Disk in the Solar neighborhood

Weight: If the disk is thin and self-gravitating, we can regard it locally as an infinite plane of mass/area μ and work out the weight of a star at height h above the disk:



$$dF = -\frac{Gm(2\pi r\, dr\, \mu)}{h^2 + r^2} \frac{h}{\sqrt{h^2 + r^2}}$$

M/A of the Disk in the Solar neighborhood



$$F = -\pi G \mu m h \int_0^\infty \frac{2r\,dr}{(h^2+r^2)^{3/2}} = -\pi G \mu m h \int_{h^2}^\infty \frac{du}{u^{3/2}}$$

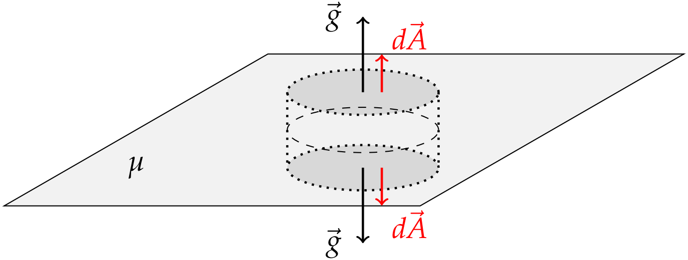
$$= -\pi G \mu m h \left[-\frac{1}{2} u^{-1/2} \right]_{h^2}^\infty = -2\pi G \mu m h \frac{1}{\sqrt{h^2}}$$

$$= -2\pi G \mu m$$

Aside: Gauss' Law

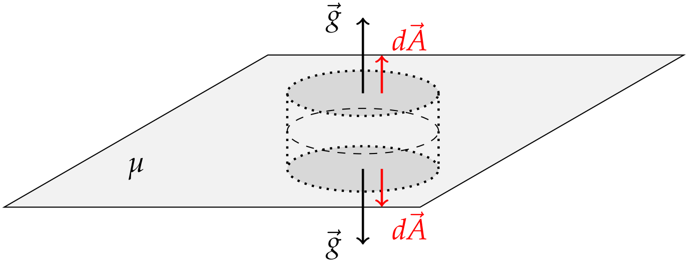
Another approach based on symmetry: **Gauss' Law**, which tells us that the flux of field lines through a surface is equal to the stuff inside:

$$\oint \vec{E} \cdot d\vec{A} = 4\pi Q_{\text{in}} \qquad\qquad \oint \vec{g} \cdot d\vec{A} = -4\pi G M_{\text{in}}$$



For the infinite plane mass sheet, the "Gaussian surface" is a cylinder.

Aside: Gauss' Law



Suppose the end caps have area A, so that $M_{\text{in}} = \mu A$. Then

$$\begin{aligned}
\oint \vec{g} \cdot d\vec{A} &= -4\pi G M_{\text{in}} \\
g \cdot 2A &= -4\pi G \cdot \mu A \\
g &= -2\pi G \mu \\
F = mg &= -2\pi G \mu m
\end{aligned}$$

M/A of the Disk in the Solar neighborhood

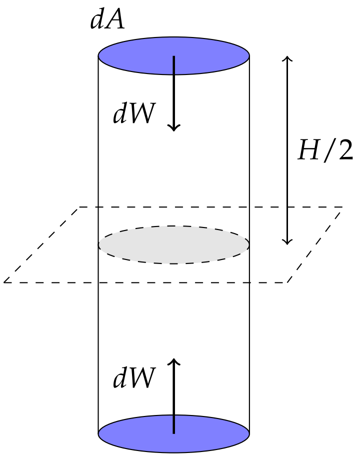
Pressure: Recall the formula for pressure in terms of number density, speed, and momentum (derived in discussion of Pauli Exclusion pressure):

$$P = \frac{F}{A} = \frac{1}{A}\frac{dp}{dt} \cong \frac{1}{A}\frac{nA\delta z}{\delta t}p_z$$
$$= nv_z p_z = \rho v_z^2$$

Consider a certain class of stars to be gas particles, and consider the component of each of their motions that is $\perp$ to the Galactic plane.

Suppose the distribution of the stars extends above and below the plane by some **scale height** $H/2$. E.g., imagine the stars are lying on the end faces of a cylinder of Galactic matter that extends one scale height above and below the plane.

M/A of the Disk in the Solar Neighborhood



Approximate weight of cylinder:

$$w = \frac{dW}{dA} = \frac{\bar{g}_z dm}{dA} = \bar{g}_z \rho H$$

If the stellar pressure balances gravity,

$$\rho v_z^2 = \rho \bar{g}_z H, \quad \text{or} \quad \bar{g}_z = \frac{v_z^2}{H}$$

From above, for a self-gravitating disk:

$$F = 2\pi G \mu m = m g_z$$

$$\Longrightarrow \quad \mu = \frac{g_z}{2\pi G} = \frac{v_z^2}{2\pi G H}$$

All terms in red are observable!

M/A of the Disk in the Solar neighborhood

Put the numbers in for the solar neighborhood:

$$\mu_\odot = 1.5 \times 10^{-3}\ \text{g cm}^{-2} = 7.2\ M_\odot\ \text{pc}^{-2}$$

Star counts in the solar neighborhood enable us to estimate the local luminosity per unit area $\mathcal{L}$ — also called the **surface brightness** — of the disk. This leads to a **mass to light ratio**

$$\left(\frac{\mu}{\mathcal{L}}\right)_\odot = 5 M_\odot L_\odot^{-1}$$

On average, the solar neighborhood emits light less efficiently than the Sun. This is consistent with there being more low-mass stars than high-mass stars.

Dark Matter? The Galactic disk in the Solar neighborhood

When this procedure was first applied to observations by Jan Oort in the 1940s, the resulting value of μ was greater than that of visible stars and interstellar gas in the Solar neighborhood by a factor of 2.

- Missing mass, or **dark matter**? I.e., mass that emits no light but can be detected by its gravity.
- Since then, better (less biased) samples of stars have led to smaller estimates of the total μ.
- The discovery of neutral atomic and molecular gas has increased the “luminous” mass a bit.
- Now the luminous and gravitating μ match within experimental uncertainties. The “disk” dark matter has vanished (e.g., Kuijken & Gilmore 1991, Flynn et al. 2006).