The Milky Way Galaxy:
Vertical Distributions of Stars & the Stellar Disk
disks exist in many astrophysical systems

we’d like to know: how they form & how they evolve

studying their detailed structure can reveal this!
Milky way galaxy in optical (0.4 -0.7μm)(B V R)

Milky way galaxy in infrared (1.2, 1.6, 2.2μm)(J H K)(2MASS)
Bandpasses used in astronomy

ultraviolet  visible  near-infrared
Disks of highly-inclined spiral galaxies

Disk of S0 galaxy

What do these images tell us about stellar disks?
good view of edge-on stellar disk in S0 galaxy

NGC 4452
HST
NGC 4565
Sb galaxy
NGC 891, a nearby galaxy similar to Milky Way, viewed edge-on
good view of edge-on stellar disk in S0 galaxy

NGC 4452
HST

stellar disk is relatively thin
disk thickness is small compared to disk radius
NGC 4565 Sb galaxy

dust (& cold gas) are disk component not bulge component
NGC 891, a nearby galaxy similar to Milky Way, viewed edge-on

compare vertical distributions of stars and dust
stellar disk thicker than dust (& gas) disk
Stellar disks often but not always associated with dust/gas disks.

Stellar bulges not associated with dust/gas.

Stellar disks generally thicker than gas disks.

Gas disks in some galaxies appear disturbed.
NGC 891, a nearby galaxy similar to the Milky Way, viewed edge-on.
How does the disk of a galaxy form?

A. dark matter settles to disk via dissipation, its dominant gravity pulls gas & stars to disk
B. gas and stars settle to disk via dissipation
C. gas settles to disk via dissipation
D. accreted gas all has same angular momentum
How does the disk of a galaxy form?

A. dark matter settles to disk via dissipation, its dominant gravity pulls gas & stars to disk
B. gas and stars settle to disk via dissipation
C. gas settles to disk via dissipation
D. accreted gas all has same angular momentum
Why does disk form?

see video.... https://www.youtube.com/watch?v=tmNXKqeUtJM#t=54.334708
compare particle orbits for:

- set of collisionless particles
compare particle orbits for:

- set of collisionless particles
- set of collisional particles, elastic collisions
compare particle orbits for:

• set of collisionless particles
• set of collisional particles, elastic collisions
• set of collisional particles, inelastic collisions, no rotation
compare particle orbits for:

- set of collisionless particles
- set of collisional particles, elastic collisions
- set of collisional particles, inelastic collisions, no rotation
- set of collisional particles, inelastic collisions, rotation
compare particle orbits for:

- set of collisionless particles → *orbits don’t change, overall shape of system doesn’t change*

- set of collisional particles, elastic collisions → *individual orbits change but average KE of orbits remains unchanged in all 3 spatial dimensions – overall shape of system doesn’t change (apart from possible redistribution in radius)*

- set of collisional particles, inelastic collisions, no rotation → *particles all sink to center*

- set of collisional particles, inelastic collisions, rotation → *results in disk*
Why rotating gas cloud forms thin rotating disk

(nearly) all *random motions* result in inelastic collisions, which dissipate energy

\[ KE_{\text{random}} \rightarrow \text{other forms of energy} \]

*ordered motions* (net rotation) do **not** result in collisions (orbits are parallel & non-intersecting)

\[ KE_{\text{ordered}} \rightarrow \text{remains } \sim \text{constant} \]

Only motions supporting cloud in directions other than rotation direction are random so if particles are collisional the cloud collapses in all directions other than rotation direction
Why rotating gas cloud forms thin rotating disk

(nearly) all random motions result in inelastic collisions, which dissipate energy

KE_{random} \rightarrow \text{other forms of energy}

this component doesn’t experience collision so motion remains
• disk must form from gas, since *gas is collisional*

• disk cannot form from stars, since *stars are collisionless*
collisional gas vs. collisionless stars

- **size**: large gas cloud vs. small star

- **mean free path**: gas particle has small mfp vs. star has large mfp (will develop more later)
How does stellar disk form?

Gas, which is collisional and dissipates energy through collisions, settles to a rotating thin gas disk.

Stars form in giant molecular clouds (GMCs) of dense gas, which are embedded within a thin disk of gas. The youngest stars are therefore in a disk with the same thickness as the layer of star-forming dense gas.
gas forms disk

gas in disk forms new stars to make stellar disk

stars that existed before assembly form stellar bulge & halo
Stellar disks often but not always associated with dust/gas disks.
you need to first form a gas disk to make a stellar disk, but after that the gas in the disk can go away.

Stellar bulges not associated with dust/gas.
bulges formed by process(es) not involving gas dissipation

Stellar disks generally thicker than gas disks.
stars form in thin disk but later things can happen to make stellar disk thicker

Gas disks in some galaxies appear disturbed.
mergers can make irregular gas disks which eventually dissipate energy and become thin
examine nearest disk: Milky Way Galaxy

- The structure of stellar disks reveals important information about their formation and evolution
- Both internal and external processes can make them thicker over time
we’d like to examine vertical structure of Milky Way disk, but we need to know distances to stars … **how do we get distances to stars?**

![Diagram showing study of stars in directions perpendicular to disk plane.](image)
Limits of parallax

(trigonometric) parallax – accurate and simple method for measuring distances to nearby stars.

- Hard to measure angles smaller than ~0.01” even from space, so this limits distances from parallax to ~100 pc.

\[
d(\text{parsecs}) = \frac{1}{p(\text{arcseconds})}
\]

\[
d \approx \frac{1}{p}
\]

\[
\text{1 AU} = 150,000,000 \text{ km}
\]

-> How do we measure distances to stars at larger distances, in order to map the stellar distribution of the galaxy? (Galaxy is > 10 kpc in size)
Suppose we have a good spectrum of a star. From the spectrum, plus its flux and temperature, plus some basic knowledge about stars, how can we determine the star’s distance?
if you somehow know distances to stars, can calculate luminosity from brightness & distance, and make HR (luminosity-temperature) diagram

observed quantities: brightness (flux) and temperature
How can we use HR diagram to estimate distances to stars?

We know the luminosity of main sequence stars of any temperature from the HR diagram of stars in the solar neighborhood, whose distances have been measured by parallax.
For stars along the main sequence, there is a ~one-to-one correspondence between surface temperature/spectral type (distance independent) and luminosity (distance dependent -- need to know distance to get luminosity from measured flux).
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→ use this to get rough estimate of distance (technique of "spectroscopic parallax" ...bad name!)
Spectra of main sequence stars

- Cool + red
- Warm + yellow
- Hot + blue
measure the color/temperature/spectral type of a star. If you know it’s on the Main Sequence, then the HR diagram tells you its luminosity! We then get distance from $d^2 = \frac{L}{4\pi f}$.
BUT … how do you distinguish Main Sequence stars from Giant stars?
How do you distinguish Main Sequence stars from Giant stars?

A. giants are not fusing Hydrogen in core
B. measure apparent size from interferometry
C. deep spectrum shows different line ratios
D. compare widths of spectral lines
How do you distinguish Main Sequence stars from Giant stars?

A. giants are not fusing Hydrogen in core
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Spectra of A stars:
main sequence vs. giant vs. supergiant

How are the spectra different?
Smaller stars (MS) have stronger surface gravity & surface pressures => broader lines
Hydrostatic Equilibrium

stars – in hydrostatic equilibrium

\[ ma = \sum F \]

Newton's 2nd law

if acceleration = 0, star in equilibrium
gravity balanced by pressure
As the radius of a star decreases, the surface gravity increases in order to balance stronger gravity. A larger pressure gradient (and larger pressure and larger density) is required.

Spectral lines emitted by particles at higher pressure are broader due to *pressure broadening*. 
Pressure Broadening is greater for the smaller, denser star. The giant star has a more tenuous atmosphere and will produce narrower spectral lines.
Now that we can measure stellar distances to many kiloparsecs with spectroscopic parallax, we can examine vertical structure of Milky Way disk.
You might think the stellar population is homogenous throughout the disk but it is not! The population changes as you go higher above the disk midplane.

This interesting complexity can help reveal how the disk formed & evolved!
Vertical distribution of stars near Sun in Milky Way

Note that the A stars have a very small scale height (main sequence A stars have age < 100 Myr)

Why do different types of stars have different vertical distributions?

G, K stars have large age range but many are old > 3 Gyr (these G&K stars are mostly giant stars – can be detected at large distances)
NGC 891, a nearby galaxy similar to Milky Way, viewed edge-on

compare vertical distributions of stars and dust
dust in thinner disk than stars
young stars are in thinner disk than older stars
compare vertical distribution of luminous blue stars (massive main sequence stars) to overall stellar disk young stars are in thinner disk than older stars
compare vertical distribution of luminous blue stars (massive main sequence stars) to overall stellar disk. Young stars are in thinner disk than older stars.
Density of stars (of particular type S) in Milky Way disk

\[ n(R, z, S) = n(0, 0, S) \exp[-R/h_R(S)] \exp[-|z|/h_z(S)] \]

Use cylindrical coordinates \((R, \phi, z)\)
and integrate over azimuthal angle \(\phi\)
assume cylindrical coordinate system 
\((R, \phi, z)\) with no azimuthal \((\phi)\) dependence

\[n(R,z) \text{ number density of stars (\#stars pc}^{-3})\]

\[\rho(R,z) = M_{av} \ n(R,z) \text{ mass density of stars (M}_{sun} \ pc^{-3})\]

\[\Sigma_{\#}(R) = \int n \ dz \text{ surface \#density of stars (\#stars pc}^{-2})\]

\[\Sigma_{m}(R) = \int \rho \ dz \text{ surface mass density stars (M}_{sun} \ pc^{-2})\]

\[M(<R) = \int \int \Sigma \ d\phi \ dR = \int \int \int \rho \ d\phi \ dR \ dz \text{ total mass within radius } R \text{ of all stars}\]

a version of each of these equations can be written each sub-type of star by including an S
assume cylindrical coordinate system $(R, \phi, z)$ with no azimuthal ($\phi$) dependence

$n(R, z, S)$ number density of stars of type $S$ (#stars pc$^{-3}$)

$\rho(R, z, S) = M_{av} n(R, z, S)$ mass density of stars, type $S$ (M$_{sun}$ pc$^{-3}$)

$\Sigma_\#(R, S) = \int n \, dz$ surface #density of stars, type $S$ (#stars pc$^{-2}$)

$\Sigma_m(R, S) = \int \rho \, dz$ surface mass density stars, type $S$ (M$_{sun}$ pc$^{-2}$)

$M(<R, S) = \int \int \Sigma \, d\phi \, dR = \int \int \int \rho \, d\phi \, dR \, dz$ total mass within radius $R$ of stars of type $S$

a version of each of these equations can be written for all stars by omitting the $S$
Density of stars (of particular type S) in Milky Way disk

\[ n(R, z, S) = n(0, 0, S) \exp[-R/h_R(S)] \exp[-|z|/h_z(S)] \]

Use cylindrical coordinates \((R, \phi, z)\) and integrate over azimuthal angle \(\phi\)

\(h_R = \text{(radial) scale length of disk}\)

\(h_z = \text{(vertical) scale height of disk}\)

\(n(0,0,S) = \text{density of stars of type S at galaxy center}\)
Density of stars (of particular type $S$) in Milky Way disk

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

**Vertical distribution:**

- Nothing special about exponential. It gives OK rough fit for some types of stars.

- Very different scale heights for stars of different type or age. (age is main parameter, but harder to determine than type.)

- Possible to study in detail in Milky Way!
Density of stars (of particular type S) in Milky Way disk

\[ n(R, z, S) = n(0, 0, S) \exp\left[-\frac{R}{h_R(S)}\right] \exp\left[-\frac{|z|}{h_z(S)}\right] \]

Radial distribution:

• Exponential is excellent fit to light profiles of many disk galaxies. Some galaxies deviate from this.

• Scale length differences for different types of stars in some but not all disks (generally not as important as type differences in vertical distributions).

• Hard to study in Milky Way
Density of stars (of particular type S) in Milky Way disk

\[ n(R, z, S) = n(0, 0, S)\exp[-R/ h_R(S)]\exp[-|z|/ h_z(S)] \]

Use cylindrical coordinates \((R, \phi, z)\) and integrate over azimuthal angle \(\phi\)

- \(h_R = (\text{radial})\) scale length of disk
- \(h_z = (\text{vertical})\) scale height of disk
- \(n(0,0,S) = \text{density of stars of type S at galaxy center}\)

Radial distribution:
- Exponential is excellent fit to light profiles of many disk galaxies.
  - Some galaxies have deviations from this.
- Scale length differences for different types of stars in some but not all disks
  (generally not as important as type differences in vertical distributions)
- Hard to study in Milky Way

Vertical distribution:
- Nothing special about exponential, gives OK rough fit for some types of stars
- Very different scale heights for stars of different type or age
  (age is main parameter, but age is harder to determine than type)
- Possible to study in detail in Milky Way
• got only this far in lecture....
Table 2.1 Scale heights and velocities of gas and stars in the disk and halo

<table>
<thead>
<tr>
<th>Galactic component</th>
<th>$h_z$ or shape</th>
<th>$\sigma_x = \sigma_R$ (km s$^{-1}$)</th>
<th>$\sigma_y = \sigma_\phi$ (km s$^{-1}$)</th>
<th>$\sigma_z$ (km s$^{-1}$)</th>
<th>$\langle v_y \rangle$ (km s$^{-1}$)</th>
<th>Fraction of local stars</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hi gas near the Sun</td>
<td>130 pc</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Tiny</td>
</tr>
<tr>
<td>Local CO, H$_2$ gas</td>
<td>65 pc</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Tiny</td>
</tr>
<tr>
<td>Thin disk: $Z &gt; Z_\odot/4$</td>
<td>(Figure 2.9)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>90%</td>
</tr>
<tr>
<td>$\tau &lt; 3$ Gyr</td>
<td>$\approx 280$ pc</td>
<td>$27$</td>
<td>$17$</td>
<td>$13$</td>
<td>$-10$</td>
<td></td>
</tr>
<tr>
<td>$3 &lt; \tau &lt; 6$ Gyr</td>
<td>$\approx 300$ pc</td>
<td>$32$</td>
<td>$23$</td>
<td>$19$</td>
<td>$-12$</td>
<td></td>
</tr>
<tr>
<td>$6 &lt; \tau &lt; 10$ Gyr</td>
<td>$\approx 350$ pc</td>
<td>$42$</td>
<td>$24$</td>
<td>$21$</td>
<td>$-19$</td>
<td></td>
</tr>
<tr>
<td>$\tau &gt; 10$ Gyr</td>
<td>$45$</td>
<td>$28$</td>
<td>$23$</td>
<td>$30$</td>
<td>$-30$</td>
<td></td>
</tr>
<tr>
<td>Thick disk</td>
<td>0.75–1 kpc</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5%–15%</td>
</tr>
<tr>
<td>$\tau &gt; 7$ Gyr, $Z &lt; Z_\odot/4$</td>
<td>(Figure 2.9)</td>
<td>$68$</td>
<td>$40$</td>
<td>$32$</td>
<td>$-32$</td>
<td></td>
</tr>
<tr>
<td>$0.2 \lesssim Z/Z_\odot \lesssim 0.6$</td>
<td>$63$</td>
<td>$39$</td>
<td>$39$</td>
<td>$-51$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Halo stars near Sun</td>
<td>$b/a \approx 0.5$–0.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$\sim 0.1%$</td>
</tr>
<tr>
<td>$Z \approx Z_\odot/50$</td>
<td>$140$</td>
<td>$105$</td>
<td>$95$</td>
<td>$-190$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Halo at $R \sim 25$ kpc</td>
<td>Round</td>
<td>$100$</td>
<td>$100$</td>
<td>$100$</td>
<td>$-215$</td>
<td></td>
</tr>
</tbody>
</table>

Note: gas velocities are measured looking up out of the disk ($\sigma_z$ of Hi), or at the tangent point ($\sigma_\phi$ for Hi and CO); velocities for thin-disk stars refer to Figure 2.9. For thick disk and halo, abundance $Z$, shape, and velocities refer to particular samples of stars. Velocity $\langle v_y \rangle$ is in the direction of Galactic rotation, relative to the local standard of rest, a circular orbit at the Sun’s radius $R_0$, assuming $v_{y,\odot} = 5.2$ km s$^{-1}$.
Key points of table 2.1

• scale height of disk stars increases with age of stars

• increase in scale height corresponds to increase in velocity dispersion and decrease in mean rotational velocity

• There are different velocity dispersions in different directions (R, φ, z) *why?*

• Halo is not part of disk, and its origin is physically distinct. But there are halo stars located in the solar neighborhood and within the disk.
Nearby main sequence F and G stars

$O = \text{low metallicity stars (Z < 0.25 Z}_{\odot})$
cartoon of spiral galaxy disk showing spatial extent of stars of different ages

Thick disks result from the nested flares of mono-age stellar populations
Gas, which is collisional and dissipates energy through collisions, settles to a rotating thin gas disk.

Stars form in giant molecular clouds (GMCs) of dense gas, which are embedded within a thin disk of gas. The youngest stars are therefore in a disk with the same thickness as the layer of star-forming dense gas.
Evolution of stellar disks

• Gravitational interactions between stars and either GMCs or spiral arms transfer energy to the stars, “heating them up” dynamically, thereby increasing their vertical motions and their average height above the disk midplane

  internal, continuous process

  origin of gradual trend of increasing velocity dispersion with age of stars

• Mergers of (small) galaxies with the Milky Way galaxy gravitationally disturb the stars in the disk, “heating them up” dynamically & maybe forming new stars in a disturbed & thicker gas disk

  external, discrete random events

  origin of “thick disk”
video of thick disk formation from merger....

https://www.youtube.com/watch?v=UuaLArnj0os
disks exist in many astrophysical systems

planetary rings $10^{10}$ cm

planets around stars $10^{15}$ cm

AGN accretion disk $10^{16}$ cm

galaxy stellar disk $10^{22}$ cm

why doesn’t the universe have any larger disks?
Why don’t clusters of galaxies have disks?

A. they don’t have enough gas  
B. their gas can’t cool  
C. disk forms but gets disrupted by tidal encounters  
D. dark matter doesn’t form disks  
E. not enough time to form them