Astro 350

Lecture 9

February 7, 2022

Announcements:

- **Discussion Question 3** due next Wednesday
- **Homework 3** due Friday
- Office Hours after class Wednesday

Last time: stars–a first look

Q: for a light bulb: what is the luminosity? the flux?

Q: the Sun vs other stars: luminosity, mass?

our Milky Way Galaxy

Q: View on the sky? in 3D space?

Q: Where are we in the Milky Way? How do we know?

luminosity vs flux:

- light bulb: luminosity L is “wattage” – emitted power
  rate of energy flow out
  intrinsic to the bulb
- light bulb: flux F is intensity – apparent brightness
  depends on luminosity but also observer distance
- same for stars: seen at distance D, flux $F = L/4\pi D^2$

the Sun: mass and luminosity are in the midst of range for stars
the Sun is a typical star!

the luminous Milky Way–a great circle on the sky
  a disk in 3D space
our location: not at center, towards the outer parts of the disk

Observed Milky Way Structure

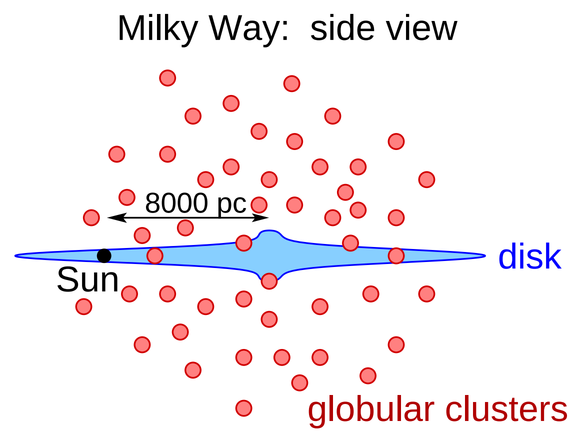
Structure: **disk** + **spherical "halo"**

Milky Way Disk: most of luminous matter

radius around $R \sim 15,000$ pc $= 15$ kpc

(with 1 kpc $=$ kiloparsec $=$ 1000 pc)

thickness $h \sim 200$ pc at our location:



the Milky Way disk is very thin!

Disk Components

1. disk contains most MW *stars*

   MW contains about $10^{11} = 100$ billion stars

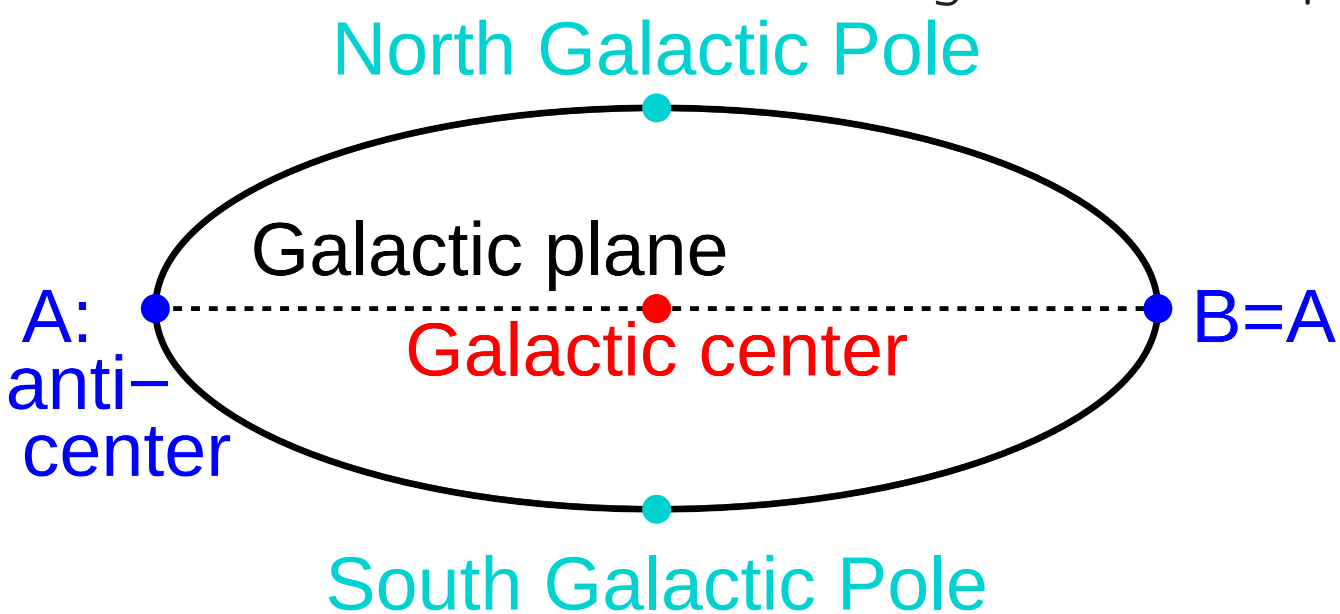
2. also *dust, gas* $\rightarrow$ fuel for star formation

   and some is the remains of stellar deaths in the past

Milky Way and All-Sky Maps

Galactic Coordinates: flattens celestial sphere onto page oriented with Milky Way

- equator: plane of MW disk
- center: towards MW center
- anti-center: opposite MW center
- note: leftmost side is *same* as rightmost: wraps around!



Convenient for seeing Milky Way features

Milky Way Disk

`www: all-sky infrared: dust, stars.`

note–confirms our suburban location!

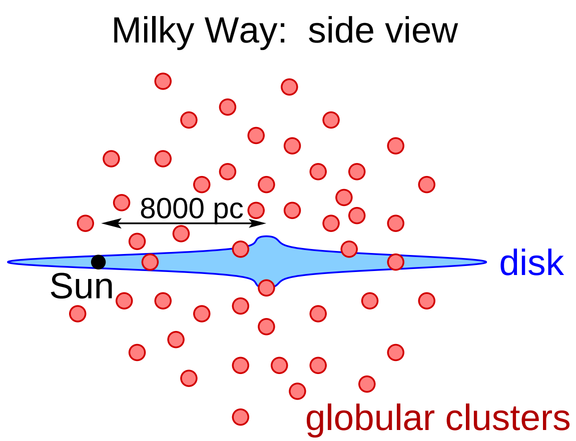
Disk Structure

- disk thickest in center, tapers off outward
- disk shows evidence for spiral arms

  $\rightarrow$ we are spiral galaxy! (as in `www: M104`)

Milky Way Spherical Components

1. bulge at center (old stars, can see in DIRBE image)
2. globular clusters
3. "halo" of old stars



Milky Way Dynamics

in MW, all objects exert gravity on all others
$\rightarrow$ everything accelerating
$\rightarrow$ everything is in motion

measure speeds of stars, gas via Doppler effect
complication: we are moving too

orbit patterns emerge

Milky Way Rotation

stars orbit MW center
disk stars: $\sim$ circular orbit $\rightarrow$ **the disk rotates!**
but disk stars *don't* spin like frisbee (i.e., a solid object)
Demo: frisbee: rigid rotation
in time Sun goes around once
stars closer to center go around more than once
stars further out — less than once
$\rightarrow$ "differential rotation"

how measure rotation speeds?
use halo stars, globular clusters (don't rotate)
Sun orbit speed: $v_{\odot} = 220/\mathrm{km/sec} = 490,000$ mph
at our location $R_{\odot} \simeq 8$ kpc (about halfway out!)

Milky Way Dynamics

Milky Way stars orbit Galactic center
orbits roughly circular

MW rotation pattern:
plot **rotation curve:** orbit speed vs distance from center

Interlude

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for experts:
rotation curves plot *linear* (well, cicular) speed v_{circ}
not angular speed $\omega = 2\pi/P$
but you can always find angular speed: $v_{\text{circ}} = \omega r$
and so $\omega = v/r$

∞

as a warmup:
Q: rotation curve for points on frisbee (all same period P)?

Poll: Solar System Rotation Curve

Rotation curve: plot orbit speed v vs distance R

What is the rotation curve shape for solar system objects?

A v increases with increasing R

B v constant with increasing R

C v decreases with increasing R

Q: why this trend?

Milky Way Rotation Curve

`www: Milky Way rotation curve data`

find $v \sim const$ beyond $R \sim 2$ kpc

"flat rotation curve"

speed stays constant (still flat) out to largest R

even when there are no more stars/gas/dust!

compare/contrast: solar system rotation curve

Q: what does the MW/SS difference mean?

Weighing the Milky Way from its Starlight

Big question: *What is the mass of our Galaxy?*

Method I: Look!

We can observe stars and gas clouds throughout the Milky Way

- stars: give most of the light we see in the MW
  and can find a star's mass using its emitted spectrum
  summing up all starlight: total $M_{\rm star} \approx 10^{11} M_\odot$ ($\odot$ =Sun)
- gas: total $M_{\rm gas} \approx 10^{10} M_\odot$, about 1/10 of mass in stars

total mas in stars & gas: $M_{\rm luminous} = M_\star + M_{\rm gas} \simeq 10^{11} M_\odot$

Q: Where is the luminous mass? How distributed in space?
Q: if sum up mass, starting outward from center, what's the result?

Where is the Mass We See?

the Galaxy's mass in stars and gas
traces the light from stars and gas

visible Galaxy is mostly in flattened disk
stars and gas extend from center ($R = 0$ kpc)
to outer edge (15 kpc)

so the mass in stars and gas should trace this shape

- if add up mass inside radius $R =$ "enclosed mass"
  at $R = 0$: enclosed mass = 0 (duh!)
  then increases as we go outward
- and at outer edge $R = 15$ kpc, enclosed visible mass
  "tops out" to constant = total mass of stars+gas: $10^{11} M_\odot$

Weighing the Milky Way from its Gravity

Method II: Find how much gravity there is

- Galaxy is rotating = accelerating, stars not free bodies
- acceleration requires force
- only important force on galaxy scales is **gravity**
  → Gravity binds the Galaxy together
- source of gravity is mass

So: study motions of stars and gas in the Galaxy
and ask: how much gravity needed cause accelerations we see
  i.e., how much mass needed to keep Galaxy from flying apart?

Milky Way Rotation Curve

`www: Milky Way rotation curve data`

find $v \sim const$ beyond $R \sim 2$ kpc

"flat rotation curve"

speed stays constant (still flat) out to largest R

even when there are no more stars/gas/dust!

compare/contrast: solar system rotation curve

Q: what does the MW/SS difference mean?

recall (HW2): orbits provide measure of gravity
stronger gravity $\rightarrow$ larger accel $\rightarrow$ faster orbits
and stronger gravity $\rightarrow$ more mass
$\Rightarrow$ orbits measure mass interior to motion

in detail (HW2): circular velocity
$v_{\text{circ}} = \sqrt{GM_{\text{enclosed}}/R}$: use to get mass interior to R
$\rightarrow M(R) = v_{\text{circ}}^2 R/G$

Solar System: $M(R) = M_\odot = const$ for all orbits
$\rightarrow$ so $v \propto 1/\sqrt{R}$: rotation curve *decreases* with R
i.e., Mercury is speedy, Pluto slowpoke

But for outer Milky Way: $v(R) = const$
Q: what does this mean for $M(R)$?

Milky Way Rotation Curve

disk stars: $\sim$ circular orbit $\to$ disk rotates

plot **rotation curve:** orbit speed vs distance

find $v \sim const$ beyond $R \sim 2$ kpc

"flat rotation curve"

Newton's gravity and Newton's laws of motion say

$$M_{\text{enclosed}}(R) = \frac{v_{\text{circ}}(R)^2 \ R}{G} \propto v^2 R \tag{1}$$

for flat rotation curves $v = const$, so

$M(R) \propto R$: Galaxy mass keeps *increasing* with R

...*even when there's no more stars/gas/dust!*

MW mass estimate (rot curves): $M_{\mathrm{MW}} = 5 - 10 \times 10^{11} M_{\odot}$ total
but stars & gas: $M_{\star} \simeq 10^{11} M_{\odot}$
$\rightarrow$ only $10 - 20\%$ of total!

Forced to conclude: a large amount of mass is unseen!
most (80-90%) of Galaxy mass
is in the form of **dark matter**!

Notice: dark matter detected by its *gravity*
- to explain motions (accelerations) of stars
  requires much more mass than meets the eye
  if only visible matter were there, rotation would be slower
- and since gravity is the force holding the Galaxy together
  visible matter alone has too little gravity
  to keep stars in circular trajectories with their observed speeds
  most stars moving fast enough to fling themselves away!

$\Rightarrow$ Without dark matter our Galaxy would fly apart!

Q: how does this revise our view of how the galaxy is built?

Dark Matter and the Structure of the Galaxy

Revised view of Milky Way structure:

- disk: most stars, all gas/dust $R_{\text{disk}} \approx 15$ kpc
- bulge/stellar halo: older stars, globular clusters
- ...but *most* of Galaxy in dark halo $R_{\text{dark}} > 50$ kpc
  Milky Way much more massive, larger, than meets the eye!

Q: what do rot curves say about the nature of dark matter?