12. The Milky Way Galaxy

1. Structure of the Milky Way

2. Generations of Stars

3. Origin and Center
The Milky Way Galaxy is a vast pinwheel of stars and gas turning within an enormous cloud of invisible matter. Many generations of stars have formed and died within its disk, enriching our galaxy’s stock of heavy elements. Before the disk formed, the future Milky Way probably existed as several distinct galaxies which fell together and merged.
1. STRUCTURE OF THE MILKY WAY

a. Layout and Populations

b. Galactic Rotation

c. Visible and Dark Mass
Layout and Populations

The Milky Way From Mauna Kea
The Milky Way: All-Sky View

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All-Sky Panorama
Our View in Perspective

We see the Milky Way as a band across the sky because we’re looking at a vast disk of stars from inside.
We can’t really see *where* we are because interstellar dust hides most of the Milky Way from our view.
Infrared light is not absorbed by dust, affording us a view of the entire Milky Way.
Globular clusters swarm around the galactic center. The MW has three main parts: bulge, disk, & halo.
Two of the Milky Way's Spiral Arms Go Missing

you are here
Two of the Milky Way's Spiral Arms Go Missing
Populations of the Milky Way

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“Our galaxy itself contains 100,000,000,000 stars / It’s 100,000 light years side to side / It bulges at the middle / 16,000 light years thick / But out by us it’s just 3,000 light years wide / We’re 30,000 light years from galactic central point... / We go ‘round . . .”

— The Galaxy Song (Monty Python)
Galactic Rotation

Most stars near the Sun have random velocities of a few tens of km/sec.

These stars orbit the galactic center at ~230 km/sec.
Stellar Orbits

Disk stars (yellow) all move in the same direction on roughly circular orbits.

Stars in the bulge (red) and halo (green) move in fairly random orbits.

Note: compare with orbits in solar system!
### Populations of the Milky Way

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This helps us understand the MW’s history . . .
Disk Galaxy Simulation

Photo-Dynamic Galaxy Model
Rotation Curves

A wheel turns with speed proportional to distance from center:

\[ v \propto r \]

In a planetary system, planets further out orbit more slowly:

\[ v \propto \frac{1}{\sqrt{r}} \]
The Milky Way’s rotation curve follows *neither* wheel-like nor planetary laws!

After rising steeply near the center, it stays roughly flat out to the last point we can measure . . .
Visible and Dark Mass

The period $P$ and radius $a$ of an orbit allow us to work out the total mass $M$:

$$M = \frac{a^3}{P^2}$$

(If $P$ is in years and $a$ in AU, get $M$ in $M_\odot$.)

In general, given the radius $r$ and speed $v$ of a circular orbit, the total mass within $r$ is:

$$M \approx \frac{r \, v^2}{G}$$

(This is exact if the mass is spherical.)

The mass within the Sun’s orbit is about $10^{11} \, M_\odot$ — twice the total mass in stars and gas within this radius!
If visible stars and gas were all, the Milky Way’s rotation curve should decline.

Most of our galaxy’s mass is invisible! Since it emits no light, it’s called **dark matter**.
The Milky Way’s total mass is at least $5 \times 10^{11} M_\odot$. More than 80% of this mass is dark.
What Is All This Stuff?

We Dunno!
2. GENERATIONS OF STARS

a. Recycling Gas and Stars
b. The Interstellar Medium
c. Where the Stars Form
Recycling
Gas & Stars

atomic hydrogen clouds
hot bubbles
molecular clouds

Star–Gas–Star Cycle

returning gas
star formation

nuclear fusion in stars

Images of galaxies and star formations.
Aging low-mass stars eject their outer layers.
Winds from high-mass stars blow bubbles of hot gas.
Supernova blast waves expand into interstellar space.
Elements made in stars are mixed back into the gas.
Bubbles blown by high-mass stars burst out of the disk.
The gas cools and falls back into the galaxy.
Cooling gas forms clouds of atomic and then molecular H.

\[ p^+ + e^- \rightarrow H \]
\[ H + H \rightarrow H_2 \]
Stars form in molecular clouds, and the cycle repeats.
Galactic Recycling Summary

- Stars fuse hydrogen, making heavier elements.
- Dying stars expel hot ($T \sim 10^6$ K) bubbles of gas.
- As gas cools ($T \sim 10^4$ K), hydrogen atoms recombine.
- Further cooling ($T \sim 30$ K) allows molecules to form.
- Gravity forms new stars in molecular clouds.
Observations at different wavelengths show different phases (ie, forms) of the interstellar medium.
The Radio Sky

Low-energy photons are emitted by free electrons

Shows hot, ionized interstellar gas and magnetic fields; ‘North Polar Spur’ is an old, nearby supernova remnant.
The 21-cm Sky

Microwave photons are emitted by H atoms

Shows warm, neutral interstellar gas clouds up to hundreds of light-years across.
The 2.6-cm Sky

Microwave photons are emitted by CO molecules

Traces cold, dense H$_2$ clouds concentrated in disk of MW; often associated with star formation.
The Far-IR Sky

Long-\(\lambda\) IR photons are emitted by warm dust

Shows star-forming regions buried in molecular clouds, and diffuse dust far from MW’s disk (red).
The Near-IR Sky

Short-\(\lambda\) IR photons are emitted by stars

Reveals cool main sequence and giant stars in MW’s disk and bulge; some dust absorption at shortest \(\lambda\)s.
The Visible Sky

Visible light is given off by stars

Bright areas are star-fields and emission nebulae; dark blobs are clouds of dust and gas.
The X-Ray Sky

Energetic photons are emitted by hot gas

Traces hot gas bubbles bursting out of the disk; point sources are X-ray binaries.
The Gamma-Ray Sky

Very energetic photons are made by cosmic rays.

Traces high gas densities and supernova remnants — and also other galaxies with central activity.
Radio
21 cm
2.6 cm
Far-IR
Near-IR
Visible
X-ray
Gamma ray

cooling

stars form

stars die
Phases of the Interstellar Medium: Summary

Cold dense gas ($T \approx 30$ K or less, $n \approx 300$ atoms/cm$^3$ or more). Most gas is in the form of molecules.

Warm gas ($T \approx 8000$ K, $n \approx 1$ atom/cm$^3$). Most of the gas is in the form of single atoms.

Hot gas ($T \approx 10^5$ K or more, $n \approx 0.001$ atom/cm$^3$ or less). Atoms are ionized (e$^-$ and nuclei are separated).
Where the Stars Form

Young, hot stars ionize the surrounding gas; glowing emission nebulae are signposts of star formation.
Light from somewhat cooler stars is scattered by dust, producing blue reflection nebulae.
Galactic Star Formation

Halo, bulge: blue stars and emission nebulae **absent** ⇒ no star formation

Disk: blue stars and emission nebulae **present** ⇒ star formation!
Spiral arms are **density waves**; they rotate more slowly than the underlying stars and gas.
Spiral Arms

bunch up

spread out

spread out

bunch up
In the disk, spiral arms are sites of rapid star formation due to compression of gas clouds as they bunch up.
Disk Galaxy Simulation
3. ORIGIN AND CENTER

a. The Collapse Scenario

b. Hierarchical Galaxy Formation

c. The Milky Way’s Center
Stellar Populations

Halo, bulge: Population II
10 — 12 Gyr old; very low ‘metal’ content

Disk: Population I
0 — 10 Gyr old; near-Solar ‘metal’ content
A giant gas cloud cools and collapses . . .

begins forming stars . . .

settles into a thin disk . . .

and continues forming stars.
Origin of Stellar Populations

Stars formed early in the collapse have random, plunging orbits and low metal content $\Rightarrow$ **Population II** (halo)

Stars formed later in the collapse are centrally concentrated and have intermediate metal content $\Rightarrow$ **Population II** (bulge)

Stars formed after the gas settles into a disk have circular orbits and high metal content $\Rightarrow$ **Population I** (disk)
Stars continuously form in the disk as the galaxy grows older.

*Warning: This model is oversimplified.*
Problems With the Collapse Scenario

1. Outer halo should be older and have less metals.
   — globular clusters show no clear trend with distance

2. Collapse to 1% of initial size needed to spin up disk.
   — time required is comparable to age of universe

3. Expect metals to build up gradually in disk.
   — oldest disk stars nearly as metal-rich as the Sun

*Does not address role or structure of dark halo!*
Scientific Method

1. Observe Nature
2. Suggest Explanation (a.k.a. Hypothesis)
3. Make Predictions
4. Trust Hypothesis (a little, anyway)

Check: True? False?
Hierarchical Galaxy Formation

Clumps of dark matter fall together and merge, building up larger and larger objects over time.
Formation of Milky Way’s Dark Halo

Builds up by repeated mergers of smaller dark halos.
Detailed studies: Halo stars formed in clumps that later merged.
Halo stars form in dwarf galaxies which are later torn apart by Milky Way’s gravitational field.
Mergers are *still* adding long streams of stars to the Milky Way’s stellar halo!
Galactic disks form by infall of gas; they’re disrupted by violent galaxy mergers.
Infalling gas is detected by 21-cm radio observations.
Hierarchical Galaxy Formation: Successes

Accretion of multiple dwarf galaxies explains ‘mixed-up’ properties of Milky Way’s stellar halo.

Disks form at centers of dark halos; problems with extreme and very slow collapse are resolved.

Continuous infall of gas allows disk to build up near-solar metal abundance early.
What lies in the center of our galaxy?
Radio emission from center

Swirling gas near center
Swirling gas near center

Orbiting stars near center

10 light-years

1 light-year
Stellar Orbits in the Central Parsec

Keck/UCLA Galactic Center Group

Stellar Orbits in the Central Parsec
Stars appear to be orbiting something massive but invisible … a black hole?

Orbits of stars indicate a mass of about 4 million $M_{\text{sun}}$. 
X-ray flares from galactic center suggest that tidal forces of suspected black hole occasionally tear apart chunks of matter about to fall in.