The Milky Way Galaxy

• “Discovery”
• Shape, Size, Components
• Spiral Structure
• Mass and Dark Matter
• The Galactic Center
• The Interstellar Medium

"There is a theory which states that if ever anyone discovers exactly what the Universe is for and why it is here, it will instantly disappear and be replaced by something even more bizarre and inexplicable. There is another which states that this has already happened."

Douglas Adams
Steps towards understanding the Milky Way

- Kant concept of “island universes”
- Herschel’s star count approach
- Kapteyn’s “Universe”
- Shapley’s distribution of globular clusters

1755: Immanuel Kant’s “Universal Natural History and Theory of the Heavens”
At the end of the 18th century, William & Caroline Herschel used the largest telescope of the era to study the shape of our Galaxy.
Toward the end of the 18th century, the Herschels began an observational survey of both the Milky Way and other star systems; a goal of this study was the determination of the shape of the stellar system we see as the Milky Way: we’ll call that the “Galaxy”.

- They counted the number of stars for each patch of sky and assumed that all stars had the same luminosity: a simple approach, appropriate for the time
- The apparent brightness of a star falls off as the inverse square of its distance; they did not know the distances of stars, but their observed fluxes yielded estimates of relative distances
- This allowed them to infer that the Galaxy had a flattened shape, that extended roughly about 5 times farther in the plane of, than in a plane perpendicular to the Milky Way
- They also compiled an extensive catalog of nebulae; they considered that some of these objects were not star systems but were "a shining fluid of a nature totally unknown to us." This catalog eventually became the New General Catalog (NGC) commonly used to identify the brightest celestial objects today
Herschel’s Model of the Galaxy

... the Solar System being located slightly off its central region
As the twentieth century dawned, photographic astronomy came into use. **J.C. Kapteyn** used the new techniques to develop a quantitative view of the structure of the Galaxy. Remember that the distances to the nearest stars were already known: **in 1838 Bessel measured the parallax of 61 Cygni**
The Nearest Stars

Bessel 1838

Diagram showing distances and positions of nearby stars, including 61 Cygni.
“Kapteyn’s Universe”

• Kapteyn got data on stats in 200 areas distributed across the whole sky: star counts, brightness estimates, spectroscopic measurements, and proper motion measurements.

• This allowed him to estimate average distances for stars at different flux levels. This analysis inferred how they are distributed in space. Just as Herschel did, Kapteyn assumed that the average brightness of stars decreases as the inverse square of their distance from us. This is not quite true as this assumption ignores the effects of absorption by the interstellar medium.

• The approach led to a picture of the Galaxy similar to that of the Herschels: as a “pancake”, about 5 times longer in the main plane of he pancake than in a direction perpendicular to the plane.

• … placing the Sun near the center of the Galaxy at a distance of approximately 650 parsecs (2100 light years).
By the end of the second decade of the twentieth century, **Harlow Shapley** proposed a new view of the cosmos...

**HOW DID HE DO IT?**

- Using a new method to estimate distances to globular cluster, Shapley estimated the distance from the Sun to the Galactic center to be on the order of 13 kpc; thus placing the Sun much further from the center than in Kapteyn's model (today's accepted value is ~8.5 kpc).
- Shapley's estimate of the radius of the Galaxy is about 4 times greater than Kapteyn's model.
- Shapley thought that the Galaxy was so large that it encompassed the entire universe.
- In 1918, the concept that spiral nebulae were actually galaxies similar to our own was still not well accepted.
Light curve of an RR Lyrae star

Luminosity-Period relation, discovered by Henrietta Leavitt

Light Curve of a Cepheid star
H. Shapley measured distribution of globular clusters far off the center of the Solar System.
(a) Artist’s view of Milky Way from afar

(b) Real image of Milky Way from inside
The problem with the Herschel/Kapteyn models of the Galaxy:

**Interstellar Extinction**
The Milky Way: Infrared view

Bulge plus disk
Possibly a bar
The Milky Way is a spiral galaxy containing about $10^{11}$ stars, most of which circle the center of the spiral.

Stars, as well as gas and dust from which stars form, are largely confined to the galactic disk. The stellar disk has a diameter of approximately 30 kpc (100,000 light years).

The stellar disk is several hundred parsecs in thickness (perpendicular to the galactic plane). Thickness depends on the age of the stellar population: the older the population, the thicker the disk they inhabit.

Close to the center of the Galaxy, a population of old stars forms a bulge.

Modern measurements place the Sun at a distance of 8.5 kpc (about 26,000 light years) from the center of the Galaxy on the inside edge of a spiral arm.
Galactic Components
Are Spiral Arms the Result of Winding Motion?

However, if spiral arms were produced by winding motion, the winding process would be too fast (a few turns, or less than 1 billion years...).
Spiral Structure and Differential Galactic Rotation

Spiral Arms cannot be the Result of Winding Motion

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What is a “density Wave”?

Imagine driving down the freeway at rush hour at 60 mph, and there is a truck doing 40 mph. Cars pile up behind the truck because the traffic density is high and there is only one free lane for passing. Cars slow down as they approach the truck; then, one at a time, they pass on the free lane and then they speed up again.

So we have a situation where the traffic jam moves along at 40 mph (the speed of the truck), while the cars on the highway well ahead and relatively far behind the truck are typically travelling at 60 mph. The density of cars is higher in the immediate vicinity of the truck. This is an example of a density wave, a density perturbation which moves along at a speed different from the speed of most objects within it.
Spiral arms of galaxies are thought to be the result of a density wave phenomenon.

The “spiral pattern” and the objects that partake of it (stars and gas) do not move at the same speed.

... like the cars travelling near a truck on the highway...
Spiral Structure in the Milky Way

The Sun lies on the inside of a spiral arm toward the outside of the disk.

Locally, spiral arms are traced by young objects: open clusters, stellar associations and HII regions.
What produces a spiral density wave?

* initial perturbations in the process of galaxy formation
* interaction with a companion galaxy

[see faceon.mpeg in A201/images]
As you see a galaxy in Blue light, spiral arms are very conspicuous: you are looking at young stars.

In red light, spiral arms are faded: you are looking at an older stellar population.

Spiral arms are sites of star formation: the compression of the gas resulting from its transit through the density wave stimulates star formation.
The Solar System rotates about the center of the Galaxy at a speed of ~ 220 km/s. The radius of its orbit is ~ 8 kpc, which is ~ 2.5 x 10^{17} km. It thus takes \( \frac{2 \pi \times 2.5 \times 10^{17}}{220} \) Myr = 6.9 x 10^{15} sec, i.e. ~ 220 million years to complete one orbit.

\( \Rightarrow \) Rotation is “differential”: rotational Period changes with radius.
The mass contained within the distance $R$ from the Galactic Center can be derived from the Rotation Curve, by using Kepler’s III Law:

$$\text{Mass (within } R\text{)} = \frac{[\text{orbital radius } R \text{ in A.U.}]^3}{[\text{orbital period in yrs}]^2}$$

- Mass within $R=8$ kpc = $10^{11}$ solar masses
- Mass within $R=20$ kpc = $3\times10^{11}$ solar masses
- Mass within $R=35$ kpc = $6\times10^{11}$ solar masses

Mass continues to increase with increasing distance from the Galactic Center.
Consider again

\[
P^2 = \frac{4\pi^2}{G(M_1 + M_2)} a^3
\]

\[
M \propto \frac{R^3}{P^2} \propto \frac{R^3}{(2\pi R / V_{rot})^2} \propto RV_{rot}^2
\]

Where \(V_{rot} \sim \text{constant}\) \(\Rightarrow\) \(M \propto R\)

i.e. the mass continues to increase (linearly) with distance from the center.
We can invert the problem and ask:

\textbf{What would the Rotation Curve of the Galaxy be like, if the mass were to be made up exclusively by the stars and the interstellar matter that we can see?}

At large distances from the center, it would drop...since we don't see it dropping, a component of matter unaccounted for by stars and ISM must be present, and its importance increases with distance from the Galactic Center.
We believe our and other galaxies are embedded within giant halos of DARK MATTER.

Halos of Dark Matter are thought to extend ~10 times the size of the visible part of a galaxy.
The rotation curve can be traced out to about 35 kpc. Within that radius the MW mass is $6 \times 10^{11}$ solar masses.

Can we trace mass even farther out?

We can monitor the motions of small galaxies ("satellites") orbiting about the Milky Way. Just like the motions of planets can be used to infer the masses within the Solar System, the mass of the galactic system can be inferred from the motions of the MW satellites.

The mass within a distance of 100 kpc from the center of the MW is $\sim 10^{12}$ solar masses.
When we take a “census” of all mass we can see (stars, interstellar gas, interstellar dust), the total is much smaller than the mass required to explain the velocities we measure.

The mass revealed by the motions it induces cannot be directly seen: it does not appear to emit any detectable radiation

⇒ *we refer to it as “DARK MATTER”*