The Milky Way Galaxy

Guiding Questions

1. What is our Galaxy? How do astronomers know where we are located within it?
2. What is the shape and size of our Galaxy?
3. How do we know that our Galaxy has spiral arms?
4. What is most of the Galaxy made of? Is it stars, gas, dust, or something else?
5. What lies at the very center of our Galaxy?

Interstellar dust obscures our view at visible wavelengths along lines of sight that lie in the plane of the galactic disk.

William Herschel maps out the distribution of stars and gets:

- The sun
- The "universe" of Herschel

What were they?
Stars & planetary systems forming in our own "universe"?
Separate "island universes"?

Henrietta Leavitt & the Cepheid P-L Relationship

- Light curve of a Cepheid variable
- Period versus magnitude of Cepheids in SMC

Large & Small Magellanic Clouds
H. Shapley maps distribution of Globular Star Clusters using “Cepheids” (“where’s the mass centered?”)

We are NOT at the center. What happened?

The Shapley-Curtis Debate (1920)

The debate solved nothing!

Questions in science are not resolved by debates, but by observations & experiments

Nature of the Spiral Nebulae and the Great Debate

Shapley

- Novae brightnesses incompatible with M31 being as big as MWG
- Rotation of M101

Curtis

- Novae indicate a smaller MWG than Shapley’s
- Galaxy proper motions undetected
- Zones of avoidance in other systems

1923 - Hubble Measures Distance to M 31 using Cepheid Variables

Shapley’s MWG was too big for a couple of reasons: Ignoring the extinction due to dust will result in deriving a photometric distance that is too large by a factor of 10^6?

But the extinction makes it fainter, so we would incorrectly think that it is HERE based on brightness measurements
Using RR Lyrae stars & Type II Cepheids, thinking they are Type I, will make the distances appear larger.

For a given apparent brightness, a higher L star must be more distant. Observed Type II’s, but used L’s of Type I’s.

Other problems:
- S Andromedae, a “nova” in the Andromeda Galaxy, was actually a supernova—with much higher L and hence distance
- Proper motions in galaxies “measured” would require speeds greater than light if they were distant—these measurements turned out to be wrong!

Summary: Shapley’s MWG was too big, and his distances to the spiral nebulae too small.

Stellar Photometric Distances

For an apparent (observed) magnitude $m$, absolute magnitude $M$, and distance $d$ in parsecs:

Without dust: $m = M + 5 \log d - 5$ and $d = 10^{\frac{m-M+5}{5}}$ pc

(reminder: $m = M_{B=10pc}$)

With dust: $m = M + 5 \log d - 5 + A$ and $d = 10^{\frac{m-M-A+5}{5}}$ pc

where $A$ is the extinction by dust in magnitudes

(Note: sometimes astronomers use the “distance modulus” $m-M = 5 \log d - 5$ to express the distance to some objects)

This dilemma was resolved by observing parts of the Galaxy outside the disk
Determining the distance and direction of the globular clusters gave us the Sun’s location. Our Sun lies within the galactic disk, some 8000 pc (26,000 ly) from the center of the Galaxy.

Observations at different wavelengths help reveal the shape of the Galaxy.

There are about 400 billion \((4 \times 10^{11})\) stars in the Galaxy.

- Our Galaxy has a disk about 50 kpc (160,000 ly) in diameter and about 600 pc (2000 ly) thick, with a high concentration of interstellar dust and gas in the disk.
- The Sun orbits around the center of the Galaxy at a speed of about 790,000 km/h.
- It takes about 220 million years to complete one orbit.

The spin-flip transition in hydrogen emits 21-cm radio waves.
This is the same physical principle behind magnetic resonance imaging (MRI), an important diagnostic tool of modern medicine.

These emissions easily penetrate the intervening interstellar dust:

21-cm emission shows that hydrogen gas is concentrated along the plane of the Galaxy.

Spiral arms can be traced from the positions of clouds of atomic hydrogen:

- Hydrogen clouds 1 and 3 are approaching us; they have a moderate blueshift.
- Hydrogen cloud 2 is approaching us at a faster speed; it has a larger blueshift.
- Hydrogen cloud 4 is neither approaching nor receding; it has no redshift or blueshift.

OB associations, H II regions, and molecular clouds in the galactic disk outline huge spiral arms.

Visible-light view of M83:

Hot luminous, young stars (blue) are in the spiral arms.
The rotation of our Galaxy reveals the presence of dark matter.

From studies of the rotation of the Galaxy, astronomers estimate that the total mass of the Galaxy is about $10^{12} M_\odot$.

$$M = \frac{r^2 v^2}{G}$$

$p$ = orbital period of the Sun
$r$ = distance from the Sun to the galactic center
$v$ = orbital speed of the Sun

(a) The orbital speed of stars and gas around the galactic center is nearly uniform throughout most of our Galaxy.

(b) If our Galaxy rotated like a solid disk, the orbital speed would be greater for stars and gas in larger orbits.

(c) If the Sun and stars obeyed Kepler’s third law, the orbital speed would be less for stars and gas in larger orbits.
Only about 10% of this mass is in the form of visible stars, gas, and dust

- The remaining 90% is in some nonvisible form, called dark matter, that extends beyond the edge of the luminous material in the Galaxy
- Our Galaxy’s dark matter may be a combination of MACHOs (dim, star-sized objects), massive neutrinos, and WIMPs (relatively massive subatomic particles)

Spiral arms are caused by density waves that sweep around the Galaxy

- There are two leading theories of spiral structure in galaxies
- According to the density-wave theory, spiral arms are created by density waves that sweep around the Galaxy
- The gravitational field of this spiral pattern compresses the interstellar clouds through which it passes, thereby triggering the formation of the OB associations and H II regions that illuminate the spiral arms

When star A has completed 1/4 of an orbit, stars B, C, and D have only completed 1/4 or less of an orbit.

After one orbit of star A, star B has completed only 1/2 an orbit and stars C and D have fallen farther behind.
• According to the theory of self-propagating star formation, spiral arms are caused by the birth of stars over an extended region in a galaxy. 
  
  – Differential rotation of the galaxy stretches the star forming region into an elongated arch of stars and nebulae.

The innermost part of the Galaxy, or galactic nucleus, has been studied through its radio, infrared, and X-ray emissions (which are able to pass through interstellar dust)
A strong radio source called Sagittarius A* is located at the galactic center. This marks the position of a supermassive black hole with a mass of about $3.7 \times 10^6 \, M_\odot$. 

### Jargon

- central bulge (of a galaxy)
- dark matter
- density wave
- disk (of a galaxy)
- far-infrared
- flocculent spiral galaxy
- galactic nucleus
- galaxy
- globular cluster
- grand-design spiral galaxy
- H I
- halo (of a galaxy)
- high-velocity star
- interstellar extinction
- Local Bubble
- magnetic resonance imaging (MRI)
- massive compact halo object (MACHO)
- microlensing
- Milky Way Galaxy
- near-infrared
- rotation curve
- RR Lyrae variable
- Sagittarius A*
- self-propagating star formation
- spin (of a particle)
- spin-flip transition
- spiral arm
- 21-cm radio emission
- weakly interacting massive particle (WIMP)
- winding dilemma