Galaxies & Introduction to Cosmology
Other Galaxies: How many are there?

- Hubble Deep Field Project
  - 100 hour exposures over 10 days
  - Covered an area of the sky about 1/100 the size of the full moon
- Probably about 100 billion galaxies visible to us!
• About 1,500 galaxies in this patch alone
• Angular size ~ 2 minutes of arc
Other Galaxies

- there are ~ 100 billion galaxies in the observable Universe
- measure distances to other galaxies using the period-luminosity relationship for Cepheid variables
- Type I supernovae also used to measure distances
  - Predictable luminosity – a standard candle
- Other galaxies are quite distant
  - Andromeda (M31), a nearby (spiral) galaxy, is 2 million light-years away and comparable in size to Milky Way
- “Island universes” in their own right
Edwin Hubble (~1924) grouped galaxies into four basic types:

- Spiral
- Barred spiral
- Elliptical
- Irregular

There are sub-categories as well.
Spirals (S)

- All have disks, bulges, and halos
- Type Sa: large bulge, tightly wrapped, almost circular spiral arms
- Type Sb: smaller bulge, more open spiral arms
- Type Sc: smallest bulge, loose, poorly defined spiral arms
Barred Spirals (SB)

- Possess an elongated “bar” of stars and interstellar mater passing through the center.
Elliptical (E)

- No spiral arms or clear internal structure
- Essentially all halo
- Vary in size from “giant” to “dwarf”
- Further classified according to how circular they are (E0–E7)
S0/SB0

- Intermediate between E7 and Sa
- Ellipticals with a bulge and thin disk, but no spiral arms
Galaxy Formation

- Not very well understood
  - More complicated than stellar formation, and harder to observe

- Formation of galaxies begins after Big Bang

- Different than star formation because galaxies may collide and merge
Galaxy Formation

• Galaxies are probably built up by mergers
  – Contrast to break up of clouds in star formation

• Our own Milky Way is eating up the neighboring Sagittarius Dwarf Galaxy
Galaxy Mergers

- Start with high density of small proto-galaxies
- Galaxies merge and turn into bigger galaxies

Actual photo (HST): lots of small galaxies
The Mass of the Galaxy

- Can be determined using Kepler’s 3rd Law
  - Solar System: the orbital velocities of planets determined by mass of Sun
  - Galaxy: orbital velocities of stars are determined by total mass of the galaxy contained within that star’s orbit

- Two key results:
  - large mass contained in a very small volume at center of our Galaxy
  - Much of the mass of the Galaxy is not observed
    - consists neither of stars, nor of gas or dust
    - extends far beyond visible part of our galaxy ("dark halo")
Galaxy Masses

- Rotation curves of spiral galaxies comparable to Milky Way
- Masses vary greatly
The Missing Mass Problem

- **Dark Matter** is dark at all wavelengths, not just visible light
- The Universe as a whole consists of up to 25% of *Dark Matter*! ➔ *Strange*!
- What is it?
  - Brown dwarfs?
  - Black dwarfs?
  - Black holes?
  - Neutrinos?
  - Other exotic subatomic particles?
- Actually: Most of the universe (70%) consists of *Dark Energy* ➔ *Even stranger*!
Missing Mass Problem

- Keplerian Motion: more distance from center → less gravitational pull → slower rotational speed
The Tully-Fisher Relation

- A relation between the rotation speed of a spiral galaxy and its luminosity.
- The more mass a galaxy has, the brighter it is, the faster it rotates, the wider the spectral lines are.
- Measuring rotation speed allows us to estimate luminosity; comparing to observed (apparent) brightness then tells us the distance.
Beyond the Galactic Scale – Clusters of Galaxies

The Local Group

The Virgo Cluster
Beyond Superclusters

- Strings, filaments, voids
- Reflect structure of the universe close to the Big Bang
- Largest known structure: the Great Wall (70 Mpc × 200 Mpc!)
Latest Results from the 2dF Survey

(a) The 2dF galaxy survey

2dF Galaxy Redshift Survey Team/Australian Astronomical Observatory
Cosmology

- The part of astronomy (and astrophysics) that deals with the greatest structures in the universe – and the evolution of the universe itself!
Cosmological Questions

– What is in the universe?

– How do these things interact?

– How does the universe change in time?
  • Is there a beginning?
  • Is there an end?
What’s in the Universe?

THE UNIVERSE

- clusters and superclusters
- galaxies like the Milky Way
- voids
- quasars

Big

Stars
- nebulae
- molecular clouds
- star clusters

Solar System
- black holes
- pulsars

Small

Sun
- planets
- moons
- comets
- meteors
- asteroids
- dust

terrestrial
- jovian
So, why is the night sky dark?
(Olbers’ Paradox)

• Conclusion: either
  – Universe is not infinite or
  – Universe changes in time
Observation III: Everything is moving away from us!

- Measure **spectrum** of galaxies and compare to laboratory measurement
- lines are shifted towards **red**
- This is the **Doppler effect**: **Red-shifted** objects are moving **away** from us
Hubble’s Law

• The final rung on the cosmic distance ladder

• **Hubble’s observations** (1920’s):
  – Light from distant galaxies is **red-shifted**
  – The more distant the galaxy, the greater the **red-shift**

• **Interpretation:**
  – Galaxies are moving **away** from us
  – More **distant** galaxies are moving faster

• The universe is **expanding**, carrying the galaxies with it!
Doppler Shifts of Galaxies

Hubble, 1929

Hubble & Humason (1931)
Hubble’s Law

Velocity = $H_0 \times \text{Distance}$

Distance = Velocity /$H_0$

- $H_0 = (68 \pm 1)$ km/sec/Mpc is Hubble’s constant
- Compare to distance = velocity $\times$ time
- Appears the universe “exploded” from a single point in the past – the Big Bang
- Age of the universe is $1/H_0$ or about 14 billion years
Example

• Object that is 2 Mpc away recesses with
  \[ v = H \cdot d = (68 \text{ km/s/Mpc}) (2 \text{ Mpc}) = 136 \text{ km/s} \]

• Object that is receding with 27,200 km/s has distance
  \[ d = \frac{v}{H} = \frac{27,200 \text{ km/s}}{68 \text{ km/s/Mpc}} = 400 \text{ Mpc} \]