**Galaxies**

2 lessons:

1) Galaxies interact with each other.

2) 90-99% of matter in universe is invisible

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**Edwin Hubble**

Mt. Wilson Observatory (Caltech)

"tuning fork" classification

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**Elliptical (E)**

E0 round  E7 elongated

little gas and dust
few bright stars
mostly metal-poor
featureless clouds

M87 Giant Elliptical
surrounded by swarm of >500 globular clusters

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Leo I dwarf elliptical
small, nearby galaxy
resolve individual stars

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**Spiral Galaxies (S)**

contain dust, gas and hot, bright Population I stars
nuclear bulge
halos with Population II

SO galaxies have a disk
not making new stars
no bright stars to illuminate spiral arms

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Sa galaxies
little gas and dust
larger nuclear bulges
tightly wound spiral arms
Sb galaxies
intermediate between
Sa and Sc
Milky Way
Sb,Sc hot, young bright
stars in arms

Sc galaxies
large clouds
of gas and dust
small nuclear bulges
very loosely wound arms

Barred Spiral Galaxies
spiral arms from ends of a bar
SBbc NGC3351 ⇒
SBb NGC1365

Irregular Galaxies
large chaotic clouds
mixed with young
and old stars

Large Magellanic Cloud ⇒
50 pc away

typically small and faint
IC4182 ⇒

Measuring the Properties of Galaxies
if we know distance
  can calculate size/diameter and luminosity
unit megaparsec (Mpc) = $10^6$ pc = $3.26 \times 10^6$ ly = $2 \times 10^{19}$ mi

**Distance Indicators:**
  extend calibration from nearest to furthest

**Cepheids** period-luminosity relation gives absolute luminosity
  relative luminosity gives distance
  most accurate
  useful only to about 50 million ly (15 Mpc)

**Global clusters** brightest stars have magnitude -10
  extends range

**H II region** cloud of ionized hydrogen around very hot stars
  not as useful because of variability

**Planetary nebula** - central star faint, re-emitted as visible
  calibrated from nearby galaxies like Andromeda

**Supernovae explosions** about same maximum brightness
  good to 1000 Mpc
  rare

**Galaxy luminosity** for different types
  very rough

**look-back time**
time in years equal to distance in light years
light reaching us now left source earlier

cluster 4-6 billion ly away
largest ~ Milky Way

**The Hubble Law**
**Doppler Effect**
  radial velocity $\Rightarrow f, \lambda$ shift
  measure $\lambda$ of spectral lines
  $\Rightarrow$ velocity
  $V_r = H d$

due to expansion of universe

**Red Shift**
HST: $H = 70$ km/s/Mpc

**Mass** most difficult quantity to determine

**Rotation Curve method**
Doppler effect
  $\Rightarrow$ velocity profile
  $\Rightarrow$ rotation periods
  $\Rightarrow$ mass (like binary stars)
Cluster Method find largest velocities in a cluster of galaxies
   calculate mass needed to keep cluster bound
Both methods give Total Mass >> mass of visible matter
   Given size and luminosity, estimate visible matter mass
   from mass-luminosity relation for stars

Dark Matter
accounts for 90-99% of all mass!
   possibly observed by gravitational distortion
   simulation
   Not normal (cold) matter.
   Possibly WIMPs - Weakly Interacting Massive Particles
      not observed in laboratory

Clusters of Galaxies few - thousands, 2700 clusters in 4\times10^9 \text{ ly}

Rich Galaxy Clusters
   \text{> 1000 galaxies}
   mostly elliptical
   sphere d \sim 3 \text{ Mpc} (10^7 \text{ ly})

   Coma Cluster
   visible - Xray

Virgo Cluster
   nearest
   \text{> 2500 galaxies}
   relatively empty

Poor Galaxy Clusters
   \text{< 1000 galaxies}
   irregularly shaped

The Local Group
Collisions between Galaxies may dominate their evolution.

- Average separation: \( \sim 20 \times \text{diameter} \)
- Stars: \( \sim 10^7 \times \text{diameter} \)
- When galaxies collide, stars do not! But dust and gas interact, causing a burst of star formation.

**The Mice** ⇒ famous example

Collisions may last 100's of million of years. We see static pictures of a **dynamic process**. After collision, the galaxies may fall together and merge to form a new galaxy, an example of **galactic cannibalism**.

**Antennae**

NGC4038 and NGC4039

- Simulation from top
- Simulation from side

**Ring Galaxies**

- Bright nucleus with a bright ring due to a smaller galaxy.
passing perpendicular through larger

**Evolution of Galaxies**

**Ellipticals**
product of mergers triggered star formation used up gas and dust more in rich clusters

**Spirals**
few or no collisions disks are delicate retain gas and dust

**Hubble Deep Field**
10 day exposure most distant galaxies youngest more spirals smaller ellipticals