AS1001:Extra-Galactic Astronomy

Lecture 3: Galaxy Fundamentals

Galaxy Fundamentals

- How many stars are in a galaxy ?
- How did galaxies form ?
- How many galaxies are there ?
- How far apart are they ?
- How are they clustered ?
- What is the mass of a typical galaxy ?
- What is the mass density of the Universe ?

Extra-galactic Distances

For extragalactic distances, convenient unit is 1 Mpc = 10^6 pc

$$m - M = 5\log_{10}(d/\mathrm{pc}) - 5$$
$$= 5\log_{10}\left(\frac{d}{\mathrm{pc}} \times \frac{10^6\,\mathrm{pc}}{\mathrm{Mpc}}\right) - 5$$
$$= 5\log_{10}(d/\mathrm{Mpc}) + 5\log_{10}(10^6) - 5$$
$$= 5\log_{10}(d/\mathrm{Mpc}) + 25$$

Note: Still have $m = M$ at d = 10 pc

How many stars in a Galaxy ?

M31 (Andromeda), at 0.9 Mpc, has an apparent magnitude $m_V = +3.5$ mag

1) $M = m - 5\log_{10}(d/\mathrm{Mpc}) - 25 = -21.3$ mag

2) Assume $M_* = +5.5$ (Sun-like stars)

3) $F_{GAL} = n_* F_*$

$$M_{GAL} - M_* = -2.5\log_{10}\left(\frac{F_{GAL}}{F_*}\right) = -2.5\log_{10}(n_*)$$

4) $n_* = \frac{F_{GAL}}{F_*} = 10^{-(M_{GAL}-M_*)/2.5} = 10^{-(-21.3-5.5)/2.5} \approx 5\times 10^{10}$

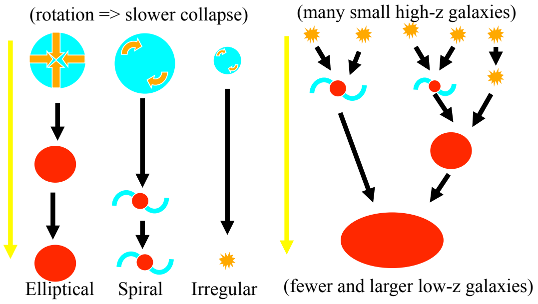
n_* = 50 billion stars

How did Galaxies Form ?

TWO COMPETING SCENARIOS

Initial Collapse: (rotation => slower collapse)

Hierarchical Merging: (many small high-z galaxies)



How did Galaxies Form?

Initial Collapse

- **For:**
  - Nearby Ellipticals are old
  - Ellipticals seen at high z
  - Spirals/Irrs rotating
  - Irregulars forming today
- **Against:**
  - Mergers are seen

Hierarchical Merging

- **For:**
  - Mergers are seen
  - More Ellipticals in high density clusters
  - HST sees more small Irrs at high z
- **Against:**
  - Some large Ellipticals seen at high z
  - Irregulars forming today

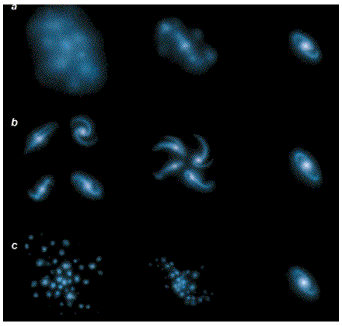
PROBABLY BOTH OCCUR

Galaxy Formation Scenarios

Initial Collapse:

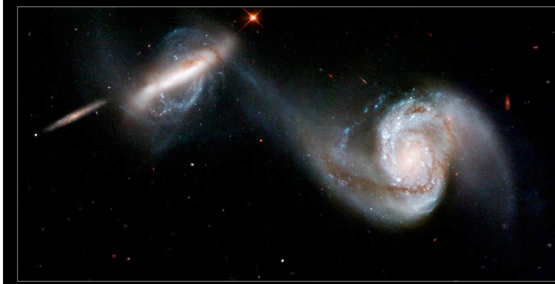
Followed by merging:

Hierarchical merging:



Colliding Galaxies

Interacting Galaxies • Arp 87

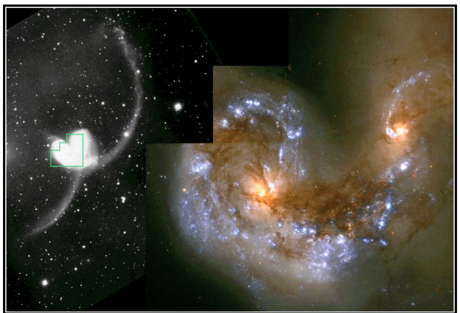


Colliding Galaxies

NGC 6050

Arp 148

The Antennae Galaxy: mid-merger



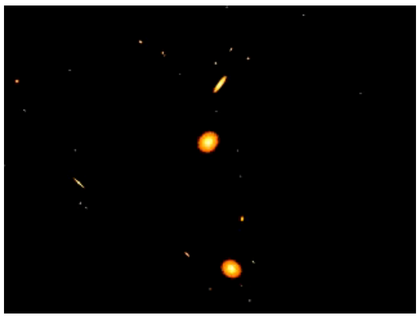
Colliding Galaxies NGC 4038 and NGC 4039 HST • WFPC2

PRC97-34a • ST ScI OPO • October 21, 1997 • B. Whitmore (ST ScI) and NASA

Coma Cluster of Galaxies

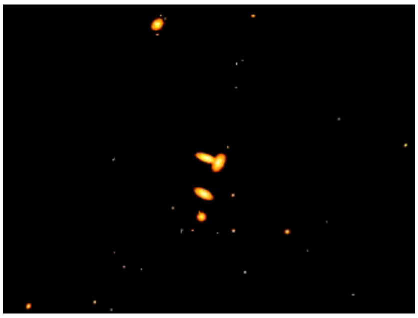
Ellipticals Dominate in Clusters

Cluster Formation Simulation



“Galactic Canibalism”: forms a giant galaxy at the cluster centre.

Cluster Formation Simulation



"Galactic Canibalism": forms a giant galaxy at the cluster centre.

How many galaxies are there ?

STEP1: Take all-sky photos

STEP2: Count galaxies brighter than some magnitude

STEP3: Assume most galaxies are like the MW*

STEP4: Calculate depth and volume of sky

STEP5: Calculate the SPACE DENSITY of galaxies

[* Big bright galaxies like the Milky Way are easiest to detect.
This does not mean they are the most numerous, just the most visible !]

Space Density of Galaxies

- **Example: The MW has $M_B = -20$ mag. There are ~10^4 MW-like galaxies brighter than 14th mag over the whole sky. How many galaxies are there per (Mpc)^3 ?**

Distance modulus equation gives the depth of the survey, i.e. the maximum distance =>

$$m - M = 5\log_{10}(d/\text{Mpc}) + 25$$

$$d = 10^{(m-M-25)/5} = 10^{(14-(-20)-25)/5}$$

$$= 63 \text{ Mpc}$$

Volume of the survey =>

$$\text{Vol} = \frac{4\pi}{3} d^3 = \frac{4\pi}{3}(63\text{Mpc})^3$$

$$= 10^6 \text{ Mpc}^3$$

n = number density

$$n = \frac{N}{\text{Vol}} = \frac{10^4 \text{gals}}{10^6 \text{ Mpc}^3} = 10^{-2} \frac{\text{gals}}{\text{Mpc}^3}$$

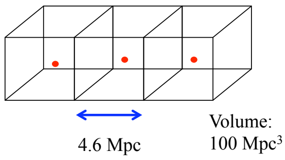
There is ~1 MW-like galaxy per 100 Mpc^3

How far apart are they ?

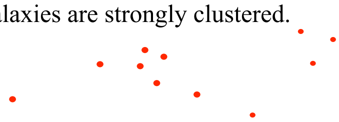
Typical separation between galaxies:

~$(100 \text{ Mpc}^3)^{1/3}$

= 4.6 Mpc



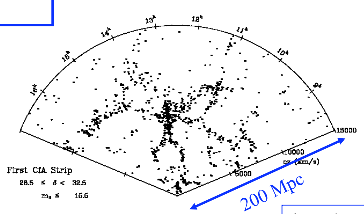
However, galaxies are strongly clustered.



Large Scale Structure

Galaxy Redshift Surveys

"The Stickman": 1980



d = v / H_0= c z / H_0

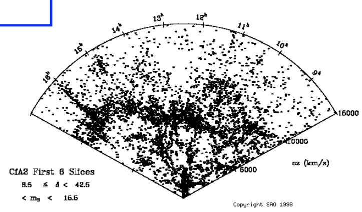
Geller & Huchra

Hubble's Law used to determine distances

Large Scale Structure

Galaxy Redshift Surveys

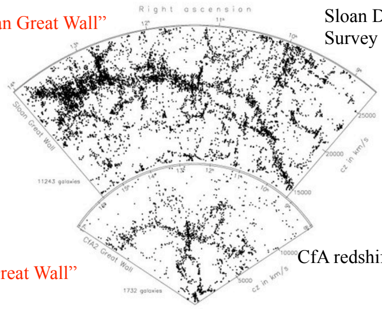
"The Great Wall": 1988



Large Scale Structure

"Sloan Great Wall"

Sloan Digital Sky Survey (SDSS)

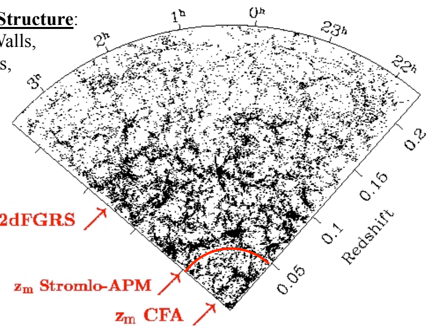


CfA redshift survey

"Great Wall"

Large Scale Structure

Bubbly Structure: Voids, Walls, Filaments, Clusters.



Mass-to-Light Ratios

- Assume that a galaxy's luminosity is proportional to its mass
- i.e., there is a **mass-to-light** ratio
- Expressed in solar units:

Mass-to-light ratio → $\frac{\mathbf{M}}{L} = X \frac{\mathbf{M}_{\otimes}}{L_{\otimes}}$ ← Solar Mass, ← Solar Luminosity

$X = 1$ for our Sun

$X \sim 10$ for a typical Galaxy

The Mass of Andromeda (M31)

M31 has $M_V = -21.3$ mag. Determine its mass assuming a "typical" mass-to-light ratio, $X = 10$.

$$\mathbf{M} = \frac{\mathbf{M}}{L} L = 10 \frac{\mathbf{M}_{\otimes}}{L_{\otimes}} L = 10\, \mathbf{M}_{\otimes} \frac{L}{L_{\otimes}}$$

$$\mathbf{M} = 10\, \mathbf{M}_{\otimes} 10^{-(M_V(\mathrm{M31}) - M_V(\mathrm{Sun}))/2.5}$$

$$\mathbf{M} = 10 \times (2 \times 10^{30}\,\mathrm{kg}) \times 10^{-(-21.3-5.4)/2.5}$$

$$\mathbf{M} = 2 \times 10^{41}\,\mathrm{kg} = 10^{11} M_{\otimes}$$

Mass Density of the Universe

- Multiply (the **space density** of galaxies)
  x (the **mass** of a typical galaxy)
  = the mass density of the Universe:

$$\rho = n\,\mathbf{M} \sim \frac{10^{11}\,\mathbf{M}_{\otimes}}{100\ \mathrm{Mpc}^3} = 10^9 \frac{\mathbf{M}_{\otimes}}{\mathrm{Mpc}^3} \approx 10^{-28}\ \mathrm{kg/m}^3$$

- This is the **luminous matter**, i.e. the stars (+gas+dust), that we can see.
- However … **"Dark Matter"** dominates.

Mass Density of the Universe

- More accurate observations (using masses from the velocities of stars inside galaxies, and of galaxies inside clusters) gives a **total density** (including **both luminous and Dark Matter**):

$$\rho \sim 3 \times 10^{10} \frac{M_{\otimes}}{\mathrm{Mpc}^3} \sim 3 \times 10^{-27}\,\mathrm{kg/m}^3$$

- Most of matter is "Dark Matter" !
- Mass of hydrogen atom: $m_H = 1.7\mathrm{x}10^{-27}$ kg
- Spread the matter smoothly, and there would be only a few hydrogen atoms per m^3.
- The air we breathe has ~ 10^{25} atoms per m^3.