Galaxies

- Galaxies are self-gravitating systems containing billions of stars and having diameters of 10–25 kpc (1 kpc = 1000 pc = 3260 lt.-yr.).
- The observed universe has billions of galaxies.
- We live in a Galaxy known as the Milky Way.
- Galaxies don’t exist randomly in space, but tend to cluster. Cluster sizes range from a few dozen members, as in our Local Group, to 10,000 like the Virgo Cluster.
- Galaxies began forming 13 Gyr ago when the universe was 1 Gyr old.
- Quasars may be young galaxies.
- Galaxies are believed to consume neighboring galaxies. The Milky Way has consumed several nearby dwarf galaxies; the Magellanic Clouds will be consumed in the near future.
- Galaxies are classified according to appearance. It’s unknown if galaxies evolved from one class into another.
- Our galaxy is a barred spiral.
Structure of the Milky Way

- The Milky Way is a barred spiral galaxy with 200-400 billion stars and $6 \times 10^{11} \, M_\odot$ of stars and gas and $6 - 30 \times 10^{11} \, M_\odot$ of dark matter.
- Major components include the nucleus (bulge), halo and disk (spiral arms.)
- The galactic center contains a supermassive black hole of $3 \times 10^6 \, M_\odot$ called Sagittarius A. Most galaxies are believed to have black holes at their centers.
- The galaxy’s nucleus is bar-shaped and about 27,000 lt.-yrs. long, and is composed of ancient red stars.
- The galaxy’s disk contains molecular clouds, young stars, and galactic clusters, largely concentrated in a ring around the bar and in 4 major spiral arms. Most current star formation occurs here. The disk diameter is about 100,000 lt.-yrs.
- Spiral arms are logarithmic spirals \( r = a e^{b\theta} \), just like the spirals in a nautilus shell or a hurricane.
- The Sun is located at the inner rim of the Orion Arm, 25,000 lt.-yrs. from the galactic center.
- The galactic halo is a spheroid of old stars and globular clusters with a diameter estimated at 200,000 lt.-yrs. The galaxy’s dark matter is uniformly distributed within the halo.
Components of the Galaxy

- Many stars in the disk are in open clusters.
- Many stars in the halo are in globular clusters.
- Molecular clouds are the birthplaces of stars and contain gas (atoms and molecules) and dust grains.
- The material between stars (99% gas, 1% dust) comprises the interstellar medium (15% of visible mass of Galaxy).
- 75% by mass of gas is H, 23% is He. Many molecules are observed, most complex ones are organic.
- Dust is composed of heavy elements and ices (H$_2$O, CO$_2$).
- Gas and dust obscure starlight.
- Some gas reflects light, some radiates light and radio waves.
- Radio emissions are used to map galactic motions and structure.
Big Bang and Cosmology

Hubble discovered in the 1920’s that the universe is expanding. This suggests that the universe began with a Big Bang. Main evidence today:

- Redshifts \((z = \frac{v}{c})\) of galaxies increase with distance: \textbf{Hubble’s Law:} \(v = H D\)

Hubble’s constant is \(H \simeq 50\) km/sec/Mpc. Note relation to \(D = vt\) which gives the age of the universe as \(t = \frac{D}{v} = H^{-1} \approx 20\) Gyr.

Universe has not expanded at a constant rate, so the true age is about 14 Gyr.

- Microwave background radiation with a uniform \(T = 2.7\) K (Predicted by Alpher, Herman and Gamow in 1948 and discovered by Penzias and Wilson in 1965, who received 1978 Nobel Prize).

This originated at the decoupling era when the universe was 300,000 yrs old and hot \((T \approx 3000\) K).

- Cosmic nucleosynthesis of light elements (He, Li, Be, B) when the universe was seconds old and hotter \((T \approx 10^9\) K). Produced composition of 75% H and 25% He by mass, observed in oldest stars.
"The whole universe is expanding, so why I surprised that we're drifting apart?"

"Hold on to your hats. We're picking up another Big Bang."

"Is that it? Is that the Big Bang?"

TRYING TO DESCRIBE THE SIZE OF THE BIG BANG

THE UNIVERSE BEFORE THE BIG BANG (ACTUAL SIZE)

BELIEVES UNIVERSE IS EXPANDING

BELIEVES UNIVERSE IS CONTRACTING

BELIEVES UNIVERSE IS STABLE
Future of the Universe

Depends upon density $d$:

$$\Omega = \frac{d}{d_c}$$

$d_c = \frac{3H^2}{8\pi G} \approx 3 \text{ H atoms/m}^3$ (critical density)

- $\Omega > 1$ ($d > d_c$): closed universe, bound, eventually recontracts.
- $\Omega < 1$ ($d < d_c$): open universe, unbound, expands forever.
- $\Omega = 1$ ($d = d_c$): critical case, expansion stalls, but no recontraction. This case is mathematically elegant, and solves the so-called flatness problem. If $\Omega$ is not exactly 1, then $\Omega$ should either be much much less than 1 or much much greater than 1 at present. Also solves horizon problem, which is why is the background radiation so uniform in all directions?

Observed abundances of light nuclei ($^1\text{H}, ^2\text{He}, ^2\text{He}, ^1\text{H}, ^4\text{Li}$) agree with theory if the density of ordinary baryonic matter (neutrons, protons and nuclei) is about 4% of the critical density ($\Omega_{\text{baryon}} \approx 0.04$). Another way of saying this is that the baryon-to-photon ratio is about $10^{-6}$. 
Density of the Universe

But measurements of our Galaxy’s mass and motions of galaxies in clusters imply a large amount of “missing mass” or “dark matter” ($\Omega_{\text{dark matter}} \approx 0.26$) that is not in the form of baryons and what form it has not is as yet unknown. Moreover, observations of

- cosmic background fluctuations
- very distant Type I supernovae

imply that

- the universe’s expansion is now accelerating, not decelerating as gravity alone would cause
- the total $\Omega$ is 1 (i.e., the universe is critical).

This implies the existence of yet another form of mass-energy, the so-called “dark energy”, with $\Omega_{\text{dark energy}} \approx 0.7$. Therefore

$$\Omega_{\text{dark energy}} + \Omega_{\text{dark matter}} + \Omega_{\text{baryon}} = 1.$$ 

Dark energy is not matter and no one knows what it could be; one suggestion is that it is the exotic matter that was proposed for faster-than-light travel.
Galaxy Cluster Abell 1689
Hubble Space Telescope • Advanced Camera for Surveys

NASA, N. Benitez (JHU), T. Broadhurst (The Hebrew University), H. Ford (JHU), M. Campbell (STScI), G. Hartig (STScI), G. Illingworth (UCO/Lick Observatory), the ACS Science Team and ESA

"Dr. Renly believes he's close to the answer. He discovered that the clusters of galaxies spell out something, but he's still missing a few letters."

S. Harris
Inflation

Conceptual problems with the Big Bang:

- Horizon: why is background radiation uniform when originates from regions that are now causally disconnected?
- Flatness: why is \( \Omega \) so close to 1, when it could have been any number?
- Smoothness: where did perturbations in nearly uniform universe originate? Without these perturbations, stars and galaxies would never have formed.
- Monopole: Magnets have two poles: why not one?
- Antimatter: Why is universe predominately matter?

Apparent Solution: Early period of rapid growth (inflation)

- About \( 10^{-36} \) seconds after birth, parts of the universe underwent massive expansions similar to weak parts of inflating balloon.
- These regions expanded so much they now appear flat (\( \Omega = 1 \)).
- All observable matter was causally connected before inflation, so it maintains uniform temperature today after inflation.
- Perturbations needed for structures inflated from quantum irregularities in pre-inflation universe.
Models of the Universe


- Spatially open
- Spatially closed

Recollapses in finite time
Expands forever
Loitering universe
Bouncing universe


Lattimer, AST 301, Big Bang Lecture – p.11/22
History of the Universe

The Planck epoch
- The quantum gravity barrier
- $T = 10^{33}$ GeV
- $t = 10^{-43}$ s

The inflationary transition
- Monopoles, baryogenesis, cosmic strings, etc.
- $G \rightarrow H \rightarrow SU(3) \times SU(2) \times U(1)$

The Particle Desert
- Electroweak phase transition
- $SU(3) \times SU(2) \times U(1) \rightarrow SU(3) \times U(1)$
- Electromagnetic & weak nuclear forces become differentiated

The transition to hadrons
- Protons & neutrons

Quark-hadron transition
- Relic radiation decouples (CBR)
- Light elements created - D, He, Li
- Epoch of gravitational instability
- Onset of matter domination
- $T = 3000$ K (1 eV)
- $t = 400,000$ years

Nucleosynthesis
- Epoch of gravitational collapse
- Solar system
- Quasars

Recombination
- Life on earth
- $T = 3K$ (1 meV)
- $t = 3$ minutes
- $t = 1$ second
- $t = 10^{-6}$ s
- $T = 1$ MeV
- $T = 10^3$ GeV
- $t = 10^{11}$ s
- $T = 10^{15}$ GeV
- $t = 10^{19}$ s

Today

www.damtp.cam.ac.uk/user/gr/public
Friedmann Equation

Conservation of Energy

\[ \frac{1}{2}mv^2 - \frac{GMm}{r} = \text{constant} \]

\[ \dot{r}^2 = \frac{8\pi G \rho}{3} a^2 - kc^2 \]

\[ H = v/r = \dot{r}/r = \frac{\dot{a}}{a} \]

\[ H^2 = \frac{8\pi G \rho}{3} - \frac{kc^2}{a^2} \]

\( k \) represents the spatial curvature. If \( k = 0 \), space is flat and \( 3H^2/8\pi G \) is the critical density. If \( k = +1 \), universe is closed. If \( k = -1 \), universe is open.

Today, \( a = 1, H = H_0, \rho = \rho_0 \):

\[ H_0^2 = \frac{8\pi G \rho_0}{3} - kc^2; \quad kc^2 = \frac{8\pi G \rho_0}{3} - H_0^2 \]

\[ H^2 = \frac{8\pi G \rho}{3} + \frac{H_0^2}{a^2} (1 - \Omega_{m0}); \quad \Omega_{m0} \equiv \frac{8\pi G \rho_0}{3H_0^2} \]

This equation holds when the pressure is 0 and the cosmological constant \( \Lambda \) is 0.
Continued

Also, note that when radiation can be ignored, $\rho \propto a^{-3}$.

Define the critical density

$$\rho_{\text{crit}} = \frac{3H^2}{8\pi G}$$

$$\Omega = \frac{\rho}{\rho_{\text{crit}}} = \frac{\Omega_{m0}}{a^3} \left( \frac{H_0}{H} \right)^2 = \frac{\Omega_{m0}}{\Omega_{m0} + (1 - \Omega_{m0})a}$$

Thus, if $\Omega_{m0} = 1$, $\Omega = 1$.

$$\int \sqrt{a} da = H_0 \int dt$$

$$a = \left( \frac{3}{2}H_0 t \right)^{2/3}, \quad t_0 = \frac{2}{3H_0}$$

If $\Omega_{m0} < 1$, $\Omega < 1$ and as $a \to \infty$, $\Omega \to 0$. Also, $k = -1$.

$$\int \frac{da}{\sqrt{\Omega_{m0}/a + 1 - \Omega_{m0}}} = H_0 \int dt$$

$$a = \frac{\Omega_{m0}}{2(1 - \Omega_{m0})}[\cosh(\eta) - 1], \quad t = \frac{\Omega_{m0}}{2(1 - \Omega_{m0})^{3/2}H_0}[\sinh(\eta) - \eta]$$
If $\Omega_{m0} > 1$,

$$a = \frac{\Omega_{m0}}{2(\Omega_{m0} - 1)} [1 - \cos(\eta)], \quad t = \frac{\Omega_{m0}}{2(\Omega_{m0} - 1)^{3/2} H_0} [\eta - \sin(\eta)]$$

This is the equation for a cycloid. $t = 0$ corresponds to $\eta = 0$. $\eta$ continuously increases with $t$, but $a$ does not. $a$ first increases, but then decreases, eventually reaching 0, then increases again.
Supernova Cosmology Project
Knop et al. (2003)

\[ \Omega_M, \Omega_\Lambda \]
0.25, 0.75
0.25, 0
1, 0

effective \( m_B \)

redshift \( z \)

supernova.lbl.gov/

Calan/Tololo & CfA
Cosmological Constant Model

Include Cosmological Constant $\Lambda$, and assume the universe is flat: $k = 0, \quad \Omega_m + \Omega_\Lambda = 1$

\[ H^2 = \frac{8\pi G \rho}{3} + \frac{\Lambda}{3} \]

Define $\Omega_\Lambda = \Lambda/(3H_0^2), \quad \Omega_m = 8\pi G \rho_0/(3H_0^2)$

\[ \int \frac{da}{\sqrt{\Omega_m/a + \Omega_\Lambda a^2}} = H_0 \int dt \]

\[ a = \left( \frac{\Omega_m}{\Omega_\Lambda} \right)^{1/3} \sinh^{2/3} \left( \frac{3}{2} \sqrt{\Omega_\Lambda} H_0 t \right) \]

\[ t_0 = \frac{2}{3H_0 \sqrt{\Omega_\Lambda}} \sinh^{-1} \left( \frac{\Omega_\Lambda}{\Omega_m} \right)^{1/2} \approx \frac{0.964}{H_0} \]

The redshift $z$ of an object is $1 + z = a^{-1}$. The distance to the horizon is

\[ r_h = \int_0^t \frac{cdt}{a} = \int_0^a \frac{cda}{a^2H} \overset{\text{since}}{=} \frac{c}{H_0} \int_0^a \frac{da}{a^{1/2}} = \frac{2c}{H_0 \sqrt{1 + z}} \]
WMAP
\[ \theta \approx z^{-1/2} = \frac{180}{\pi} z^{-1/2} \circ = 1.8^\circ \]