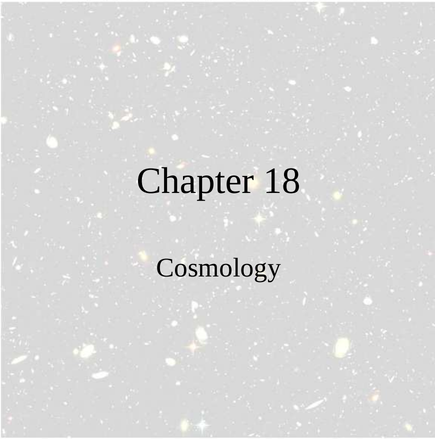
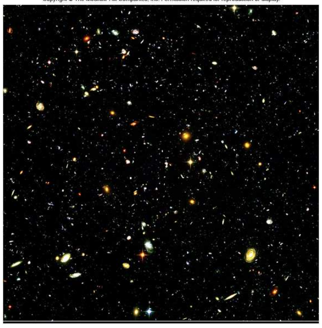


Chapter 18

Cosmology

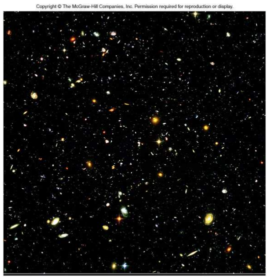
Cosmology

- ***Cosmology*** is the study of the structure and evolution of the Universe as a whole
  - How big is the Universe?
  - What shape is it?
  - How old is it?
  - How did it form?
  - What will happen in the future?



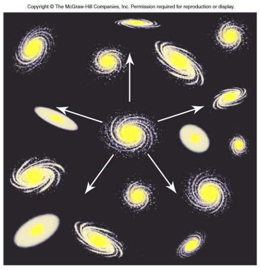
Cosmology

- What we seem to know now:
  - The Universe is expanding and is filled with a very low-energy background radiation
  - The radiation and expansion imply the Universe began some 13.7 billion years ago
  - The Universe began as a hot, dense, violent burst of matter and energy called the ***Big Bang***



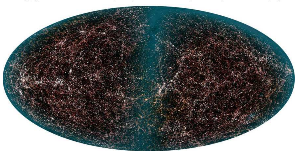
Observations of the Universe

- In the early years of the 20th century, astronomers envisioned the Universe as a static place with only the Milky Way and a few companions
- It was not until the 1920s that astronomers realized the Universe was filled with other galaxies millions of light-years apart and that the Universe was expanding



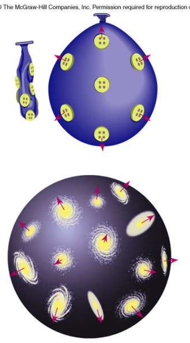
Observations of the Universe

- No matter which way you look (ignoring the zone of avoidance), you see about the same number of galaxies
- The galaxies are not spread smoothly, but clump into groups
- This “smooth clumping” implies a similar distribution for the whole Universe (contrast this with the sky’s Milky Way implying a disc-shaped galaxy)

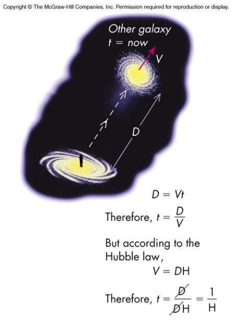


Motion of Galaxies

- In general, a galaxy obeys the Hubble law: speed of recession is proportional to the galaxy’s distance, the proportionality given by the Hubble constant
- The motion away is due to the expansion of space itself – not like bomb fragments going through the air, but like buttons attached to an expanding balloon

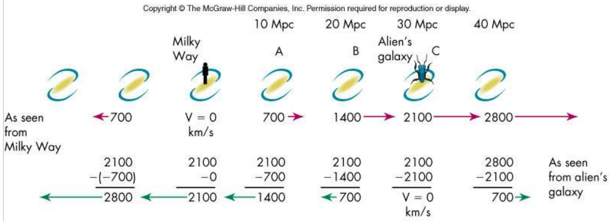


Age of the Universe



- Running the Universe's expansion backward implies all mass becomes confined into a very small volume, what was once called the "Primeval Atom"
- Assuming galaxies have always moved with the velocities they now have, the Hubble Law gives age for Universe of 14 billion years with H = 70 km/s/Mpc

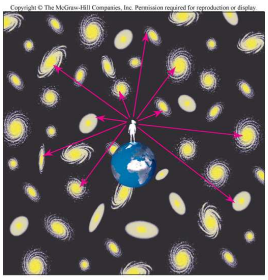
Are We at the Center of the Universe?



- The recession of distant galaxies often leads to the misconception that the Milky Way is the Universe's center
- However, because space is expanding, no matter where you are located, galaxies will move away from you – there is no preferred center
- This lack of a preferred location is called the cosmological principle

Olbers's Paradox

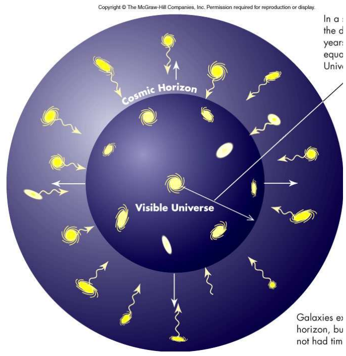
- In 1823, Heinrich Olbers offered Olbers's Paradox: If the Universe extends forever and has existed forever, the night sky should be bright – but of course it isn't
- Olbers reasoned that no matter which direction you looked in the sky a star's light should be seen



In a large enough universe, every line of sight eventually encounters a star within a galaxy

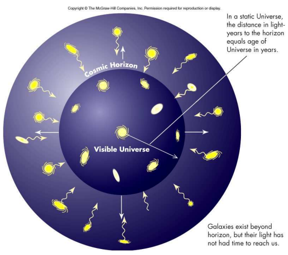
Olbers's Paradox

- Resolution: Finite age and speed of light means only a finite volume of starlight is available – the night sky is dark



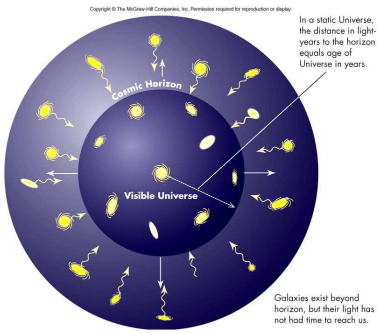
The Cosmic Horizon

- The age of the Universe limits the distance we can see since the speed of light is finite
- In a static Universe, this distance is directly determined from its age and the speed of light
- The maximum distance one can see (in principal, but not necessarily in practice) is called the **cosmic horizon**



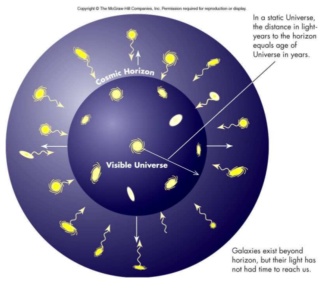
The Cosmic Horizon

- The space within the horizon is called the visible (or observable) Universe – there may very well be more to the Universe beyond



The Size of the Universe

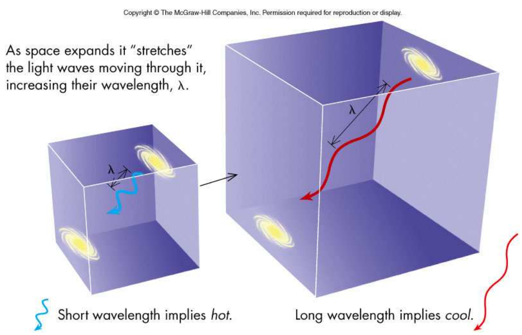
- The distance to the cosmic horizon gives a rough measure of the ***radius of the (visible) Universe***
- For a 14 billion-year-old Universe, this radius is 14 billion light-years



The Cosmic Microwave Background

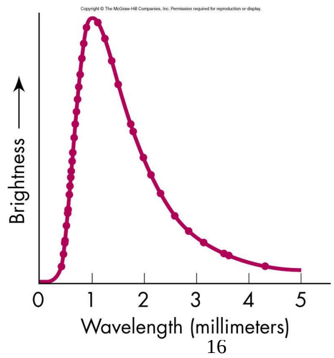
- The proposed very-dense early Universe implied that it must have been very hot, perhaps 10 trillion K
- It was proposed that as the Universe expanded and cooled, the radiation that existed at that early time would survive to the present as microwave radiation
- This radiation was accidentally discovered by Arno Penzias and Robert Wilson in 1965 and has since then been referred to as the ***cosmic microwave background*** (CMB)

"Stretching" Radiation



The Cosmic Microwave Background

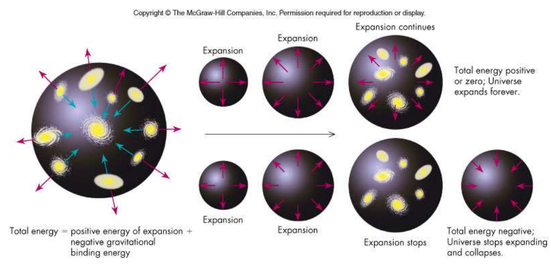
- The CMB follows a perfect blackbody spectrum with a temperature of 2.725 K (about 3 K, a bit above absolute zero)



Composition of the Oldest Stars

- Current theory suggests that the early Universe consisted of protons, neutrons, and electrons
- The initial hot and dense state allowed nuclear reactions to create helium
- Based on estimates of the early Universe's expansion rate, about 24% of the matter should be transformed to helium – in good agreement with what is observed in old stars in the Milky Way and other galaxies
- Similar measurement of deuterium (^2H) and lithium also support the hot, dense early Universe idea

Evolution of the Universe



- The Universe is currently expanding, but what of its future:
  - Will it expand forever
  - Will it stop expanding and collapse

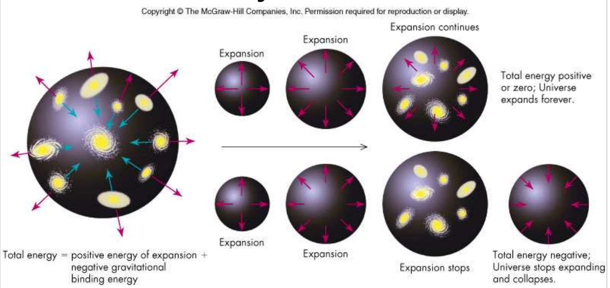
Evolution of the Universe

- Expanding forever means that as all the stars consume their hydrogen, the Universe will become black and empty – this scenario is the ***open universe***
- A Universe that collapses as a "Big Crunch" might lead to another "Primeval Atom", leading perhaps to the birth of another universe – this scenario is the ***closed universe***
- The expansion speed of the Universe becomes zero when the Universe has reached infinite size – this scenario is the ***flat universe***

Evolution of the Universe

- The energy content of the Universe depends on what type of universe we are in
  - An open universe has positive total energy
  - A flat universe has zero total energy
  - A closed universe has negative total energy
  - In principal, if we measure the energy content of the Universe, we can tell what type it is
  - The energy content of the Universe is the sum of its positive kinetic energy of expansion and its negative energy of gravitational binding (basically its mass content

The Density of the Universe



- The mass density of the Universe gives an equivalent means of determining its total energy content and it's easier to measure

The Density of the Universe

- To determine if the Universe is open or closed, compare its density (ρ) to the ***critical density***:

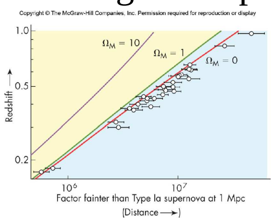
$$\rho_c = \frac{3H^2}{8\pi G}$$

- Here H is Hubble constant and G is the gravitational constant
  - If $\rho > \rho_c$, the Universe is closed
  - If $\rho < \rho_c$, the Universe is open

The Density of the Universe

- The critical density is 10^{-29} g/cm³, about one hydrogen atom per cubic meter and this is about 25 times more than the mass density determined from observed stars and gas
  - Based on the amount of observed mass, the Universe looks open
  - But if dark matter is included, the total density of the Universe is 3×10^{-30} g/cm³, almost enough to close the Universe, but not quite!

A Cosmological Repulsion?

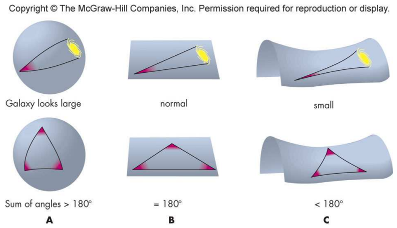


- Another way to ascertain the Universe's fate is to look at very distant galaxies – galaxies in the past – to see how fast the Universe's expansion has slowed
- Interestingly, using supernova in very far and faint galaxies as distance indicators, it appears the Universe is speeding up, not slowing down

A Cosmological Repulsion?

- How is this possible?
  - Einstein’s general relativity equations include a ***cosmological constant*** that represents a repulsive force
  - When the expansion of the Universe was discovered, the cosmological constant was thought to be zero
  - Latest measurements imply this may not be the case
  - The additional expansion energy is called ***dark energy***, and is a property of space itself.
  - This dark energy contributes to the total mass of the Universe, bringing its density up to the critical density!

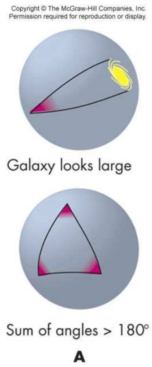
The Curvature of the Universe



- Einstein’s General Theory of Relativity is built around the ***curved space***
  - Curved space is not easy to visualize, but there are two-dimensional models that can help

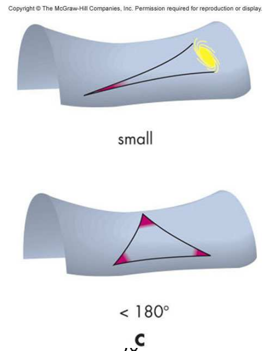
Positive Curvature

- ***Positive curvature*** (also called “closed”) resembles the surface of a sphere – parallel lines meet, and triangles have interior angles with a sum greater than 180°



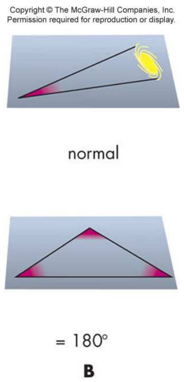
Negative Curvature

- ***Negative curvature*** (also called “open”) resembles the surface of a saddle – parallel lines never meet, and triangles have interior angles with a sum less than 180°

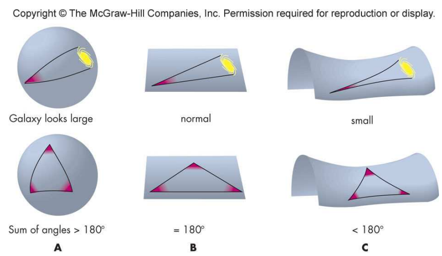


Flat Curvature

- Flat curvature (what people typically think of as space) – parallel lines do not meet, and triangles have interior angles with a sum equal to 180°

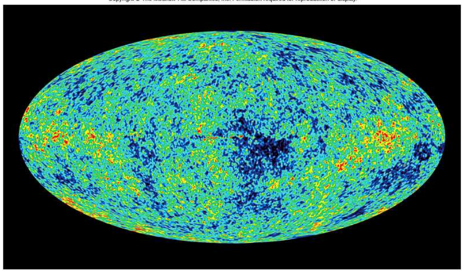


Measuring the Curvature of Space



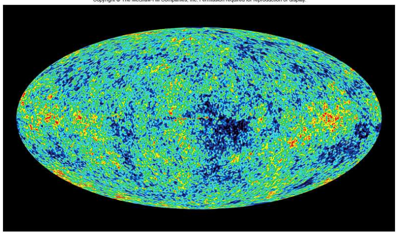
- In principle one could directly measure the interior angles of a triangle or an equivalent geometric arrangement, but to date, practical limitations prevent it

Measuring the Curvature of Space



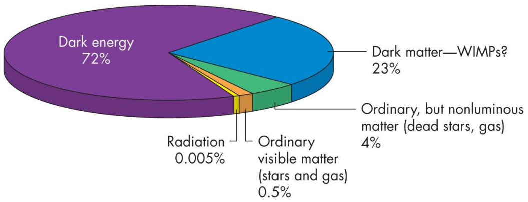
- CMB provides another way
  - CMB is extremely uniform across the sky except for tiny variations in brightness from place to place

Measuring the Curvature of Space



- The spatial sizes of these variations can be predicted based on conditions in the early Universe
- Analysis of variations indicate that Universe is flat with a non-zero cosmological constant

Makeup of the Universe



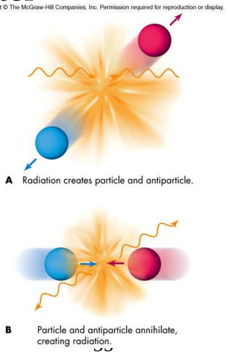
Based on observation of temperature fluctuations in the Cosmic Microwave Background, we can estimate the mass content of the Universe

The Origin of the Universe

- The early Universe's high temperature and density imply that it may have had a very simple structure
  - Mass and radiation mingled in a manner unlike their sharp distinction today
  - Radiation is so energetic that it easily transforms to mass – mass and radiation behaved as a single entity

Radiation, Matter, and Antimatter

- $E = mc^2$ tells us not only can mass be transformed to energy (as in stars), but that energy (in photons) can be transformed into mass
  - The creation of mass, however, must come in pairs, ordinary matter, and ***antimatter***
  - The antiparticle of the electron is the positron, the antiparticle of the proton is the antiproton

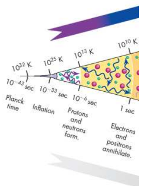


A Radiation creates particle and antiparticle.

B Particle and antiparticle annihilate, creating radiation.

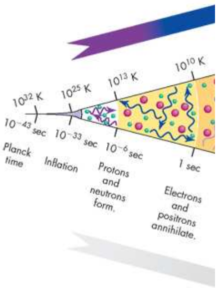
History of the Universe

- At one microsecond after the Big Bang
  - Temperature 10^{13} K, hot enough for photons to create quarks and antiquarks
  - Diameter smaller than Earth's orbit
  - Universe expands at near speed of light and cools
  - Lower temperature no longer produces quarks/antiquarks
  - Subatomic physics dictates that existing quarks/antiquarks annihilate asymmetrically leaving an excess of quarks
  - Surviving quarks combine into protons, neutrons



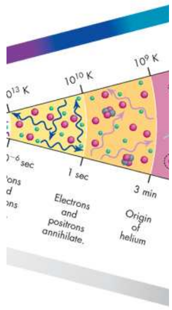
History of the Universe

- After 5 seconds or so, the Universe cools enough for the creation of matter to cease



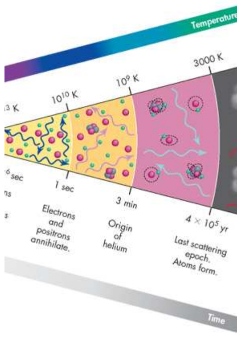
History of the Universe

- At 3 minutes after the Big Bang
  - Temperature is a few hundred million degrees
  - 1/4 of protons fuse into helium



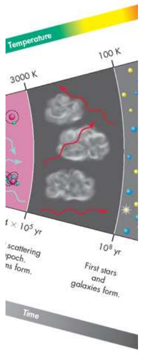
History of the Universe

- Next half million years
  - Further expansion and cooling
  - Electrons begin to bind to protons to make hydrogen molecules (this is referred to as the recombination era)
  - At end of period, photons and matter go their separate ways



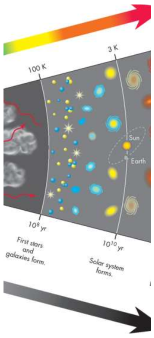
History of the Universe

- Considering ages of several galaxies, galaxy formation had to start soon after recombination era
- Protogalaxies formed from gravitational collapse of gas clouds

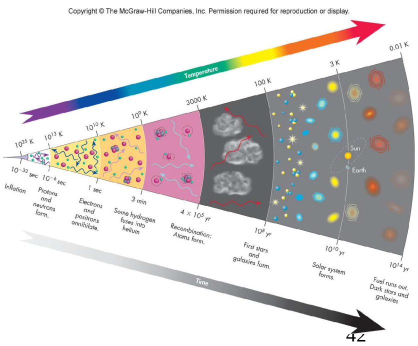


Formation of Galaxies

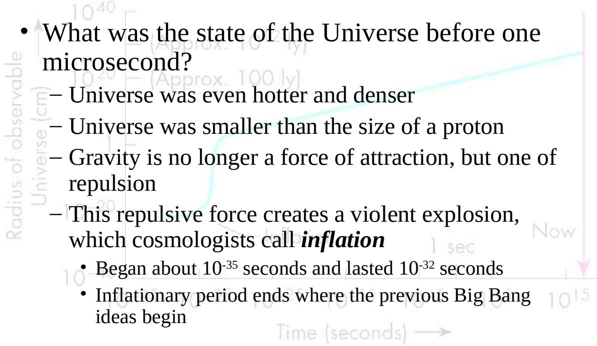
- Gravity too feeble to create galaxies in time scales needed
- Need for dark matter to speed things up
- Dark matter forms clumps around which the protogalaxies form
  - Areas rich in dark matter clumps form large scale galaxy chains and sheets
  - Area depleted in a dark matter form voids



History of the Universe

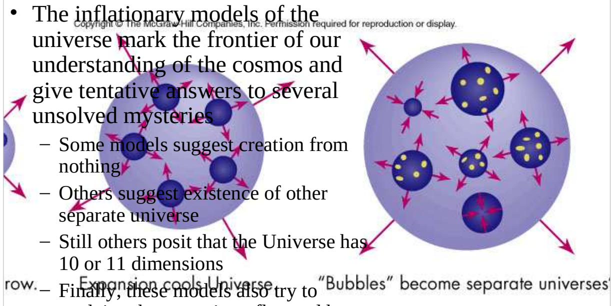


The Inflationary Universe



- What was the state of the Universe before one microsecond?
  - Universe was even hotter and denser
  - Universe was smaller than the size of a proton
  - Gravity is no longer a force of attraction, but one of repulsion
  - This repulsive force creates a violent explosion, which cosmologists call ***inflation***
    - Began about 10^{-35} seconds and lasted 10^{-32} seconds
    - Inflationary period ends where the previous Big Bang ideas begin

The Inflationary Universe



- The inflationary models of the universe mark the frontier of our understanding of the cosmos and give tentative answers to several unsolved mysteries
  - Some models suggest creation from nothing
  - Others suggest existence of other separate universe
  - Still others posit that the Universe has 10 or 11 dimensions
  - Finally, these models also try to explain why space is so flat, and how all the forces of nature relate to one another