Astronomy 100
Exploring the Universe
Tuesday, Wednesday, Thursday

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Mass-to-Light Ratio

• You can compare the measured mass to the luminosity of a galaxy
Milky Way

• Milky Way contains 90 billion solar masses of material within the Sun’s orbit
• Luminosity of Milky Way at this orbit is 15 billion solar luminosities
• Mass-to-Light ratio of our Galaxy at this orbit is 6 solar masses per solar luminosities
This tells us that …

• The value of 6 solar masses per solar luminosity tells us that most of the matter is dimmer than the Sun out to the Sun’s orbit

• Mass-to-Light ratio of our Sun is 1 solar mass per solar luminosity

• So most matter is dimmer than the Sun
For some galaxies, they have mass-to-light ratios of 50 solar masses to solar luminosity. This is too high to be accounted for by stars alone.
Fritz Zwicky (1898-1974)

- Was among the first to suggest that there is a relationship between supernovae and neutron stars
- Suggested in the 1930s that dark matter was found in Galactic Clusters
Cluster

• Cluster is a collection of galaxies (that can number dozens to thousands) that are gravitationally bound
Zwicky

• By calculating the speed of galaxies as they rotate around in a cluster
• He found that galaxies in the clusters had huge mass-to-light ratios
Types of Dark Matter

- MACHOs
- WIMPS
MACHOs

- Massive Compact Halo Objects
- Includes
  - Brown Dwarfs – failed stars
  - Faint red stars
  - Jupiter-sized objects
WIMPs

• Weakly interacting massive particles
  – No electrical charge
  – Do not emit electromagnetic radiation
  – Have mass so do interact some with matter
Neutrinos

- Dark matter in galaxies can’t be neutrinos because neutrinos escape from galaxies with enormous speeds
WIMPS

- Have to have masses larger than neutrinos
- Have not been discovered yet
Dark Energy

• Gravity should be slowing the expansion of the universe down
• However the universe appears to be accelerating
• Dark Energy is the name for what is causing the expansion to accelerate
• http://www.nasa.gov/centers/marshall/mov/100452main_accel_expanding_univ_sm.mov
Two teams of astronomers were looking for distant type Ia supernovae in order to measure the expansion rate of the universe with time.

They expected that the expansion would be slowing (due to gravity) which would be indicated by the supernovae being brighter than their redshifts would indicate.

Instead, they found the supernovae to be fainter than expected.

The universe appears to be expanding.
Supernova Ia

• Are exploding white dwarfs
• Have the same masses when they explode
• Have the same peak luminosities
• These supernovas are bright enough to be seen in far-away galaxies
• Measuring the brightness of Supernova Ia’s allows you to calculate the distance to the Supernova
• Measuring the Doppler Shift of the spectral lines of the Supernova allows you to calculate the speed the object is moving away
Supernova Ia

• The ones with the highest redshifts were dimmer than expected
• That means they were farther away than expected
• Something had caused the universe to expand faster than expected
• You would expect gravity to cause the universe to stop expanding and start decelerating
• It appears the universe is accelerating
Olber’s paradox

• How can the night sky be dark if the universe is infinite and full of stars?
Answer?

- We can only see a finite number of stars
- Looks like the Big Bang theory works:
- The universe began at a particular time
4 Forces that operate in the universe

- Gravity
- Electromagnetism
- Strong Force
- Weak Force
<table>
<thead>
<tr>
<th>Force</th>
<th>Strength</th>
<th>Range (m)</th>
<th>Particle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strong</td>
<td>$1$</td>
<td>$10^{-15}$ (diameter of a medium-sized nucleus)</td>
<td>Gluons, pions, nucleons</td>
</tr>
<tr>
<td>Electromagnetic</td>
<td>$\frac{1}{137}$</td>
<td>Infinite</td>
<td>Photon, mass = 0, spin = 1</td>
</tr>
<tr>
<td>Weak</td>
<td>$10^{-6}$</td>
<td>$10^{-18}$ (99.1% of the diameter of a proton)</td>
<td>Intermediate vector bosons, mass &gt; 80 GeV, spin = 1</td>
</tr>
<tr>
<td>Gravity</td>
<td>$6 \times 10^{-39}$</td>
<td>Infinite</td>
<td>Graviton, mass = 0, spin = 2</td>
</tr>
</tbody>
</table>
Gravity

- Massive particles interact with other massive particles
- Acts on big distances
Electromagnetism

- Charged particles act with other charged particles
- Act on small distances
Strong Force

- Force that holds atomic nuclei together
- Keeps protons together in a nucleus
- Protons would fly apart
- Occurs over very small distances like diameters of nuclei
These two types of particles are the two basic constituents of matter.

<table>
<thead>
<tr>
<th>The Quarks</th>
<th>The Leptons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Up</td>
<td>Electron</td>
</tr>
<tr>
<td>Down</td>
<td>Electron neutrino</td>
</tr>
<tr>
<td>Strange</td>
<td>Muon</td>
</tr>
<tr>
<td>Charmed</td>
<td>Mu neutrino</td>
</tr>
<tr>
<td>Top</td>
<td>Tauon</td>
</tr>
<tr>
<td>Bottom</td>
<td>Tau neutrino</td>
</tr>
</tbody>
</table>

Table S4.1 Fundamental Fermions
proton

two up quarks
one down quark

neutron

one up quark
two down quarks

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Weak Force

- Weak forces govern nuclear reactions
- Occurs over distances 0.1% the diameter of a proton
- The weak interaction changes one flavor of quark into another.
Big Bang

- The event that gave birth to the universe
- One consequence of the Big Bang is that the conditions of today's universe are different from the conditions in the past or in the future.
The Name

- Fred Hoyle proposed an alternative Steady State model in which the universe was both expanding and eternal.
- Hoyle christened the theory, referring to it disdainfully in a radio broadcast as "this 'Big Bang' idea".
Planck Time

- $10^{-43}$ seconds after Big Bang
- Before Planck Time, the universe was concentrated in a single point
- At Planck Time, the universe was $10^{32}$ Kelvin and it had the size of $10^{-33}$ cm.
Before Planck Time

- Before a time classified as a Planck time, all of the four fundamental forces are presumed to have been unified into one force.
- All matter, energy, space and time are presumed to have exploded outward from the original singularity.
- Nothing is known of this period.
• http://en.wikipedia.org/wiki/Graphical_timeline_of_the_Big_Bang
Video

Sounds

- [http://staff.washington.edu/seymour/altvw104.html](http://staff.washington.edu/seymour/altvw104.html)
GUT Era

- Lasts from $10^{-43}$ until $10^{-38}$ seconds after Big Bang
- GUT – Grand Unified Theory
- At high enough temperatures, electromagnetism, strong force, and weak force all act as one force
- Gravity still acts separately
Inflation

• During GUT era, there was inflation
• Rapid expansion of universe
Electroweak era

- Lasts from $10^{-38}$ until $10^{-10}$ seconds after Big Bang
- Strong Force becomes separated
- Left with Electroweak force
Particles being created and destroyed

Particle creation

- gamma-ray photon
- electron
- gamma-ray photon
- antielectron

Particle annihilation

- antielectron
- electron
- gamma-ray photon
- gamma-ray photon
Particle Era

- Lasts from $10^{-10}$ until 0.001 seconds after Big Bang
- Quarks, electrons, neutrinos formed
- Quarks started to make protons and neutrons and antiprotons and antineutrons
Antimatter

- Particle with same mass as ordinary particle but other basic properties are precisely opposite
Big Question

- If there were equal numbers of protons and antiprotons
- And neutrons and antineutrons
- All the particles would have annihilated each other
- Creates photons
Must have

• There must have been a very slight excess of matter over antimatter
• Like for every one billion antiprotons
• There were one billion and one protons
• So the billion antiprotons annihilated the billion protons
• Left one proton
Era of Nucleosynthesis

- Lasts from 0.001 seconds to 3 minutes after Big Bang
- Fusion started to occur
- 75% of the universe was hydrogen
- 25% of the universe was helium
Era of Nuclei

- Lasts from 3 minutes to 380,000 years after Big Bang
- Cool enough so hydrogen and helium could capture electrons
- Photons stopped hitting electrons and instead were able to stream through the universe
Era of Atoms

- Lasts from 380,000 to one billion years after Big Bang
- Protogalactic clouds start to form
Era of galaxies

• Lasts from one billion years after Big Bang to present
• Galaxies form
Evidence for Big Bang

• Cosmic Microwave Background is the form of electromagnetic radiation that fills the whole of the universe.
COBE
Cosmic Background Explorer
Measured thermal background of sky
Sky has temperature of 2.73 K
Due to

- Photons that streamed out during the era of nuclei had temperature of 3,000 K
- Had blackbody spectrum
- Has temperature now of 2.73 K since universe has expanded and stretched the wavelength of the photons
Brighter regions are 0.0001 K hotter
Importance

• This 2.73 K is very uniform across the sky
• Permeates the whole sky
• Evidence for Big Bang
Other evidence

- Predicted to have produced 75% hydrogen and 25% helium during the era of nucleosynthesis
- That is approximately what we see today
End of Universe

• Critical Density – Density marking the dividing line between eternal expansion and eventual collapse
• Dark energy started its long history in 1917 and was introduced by Albert Einstein. A constant (which he called $\Omega$) was needed in his equations of General Relativity in order to allow for a static Universe, where space is not expanding.
Hubble witnesses a cosmic tug of war

Hubble has detected that dark energy and dark matter have been at odds with one another since the early universe. As time progresses, dark energy gains the upper hand and the universe expands.
The more shallow the curve, the faster the rate of expansion. The curve changes noticeably about 7.5 billion years ago, when objects in the universe began flying apart as a faster rate. Astronomers theorize that the faster expansion rate is due to a mysterious, dark force that is pulling galaxies apart.

http://science.hq.nasa.gov/universe/science/images/dark_expansion.jpg
Robert Frost Poem

- Some say the world will end in fire,
  Some say in ice.
  From what I've tasted of desire
  I hold with those who favor fire.
  But if it had to perish twice,
  I think I know enough of hate
  To say that for destruction ice
  Is also great
  And would suffice.
Future fates of the dark-energy universe

Big Bang

Current universe

- Big Crunch: Quintessence in which dark energy reverses
- Indefinite expansion: Cosmological constant
- Big Rip: Quintessence in which dark energy destabilizes

http://www.nasa.gov/images/content/56197main_dark_schematic-lg.jpg
Recollapsing or Closed Universe

- Lacking the repulsive effect of dark energy
- Gravity eventually stops the expansion of the universe
- The Universe starts to contract until all matter in the universe collapses to a point
- Called the Big Crunch
Critical or Flat Universe

- No dark energy
- Expands Forever
- Expands more slowly
Coasting or Open Universe

- No dark energy
- Keeps on expanding forever
- Little change in the rate of expansion
Accelerating Universe

- Dark Energy
- Expansion rate increases
• http://www.nasa.gov/centers/marshall/multimedia/video/2004/video04-144.html
http://www.220.ro/documentare/BBC-The-Planets-Life-Ep-7-8/J433s66jfk/
Any Questions?