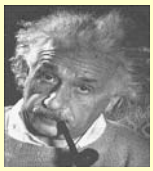
Lecture 25: Modern Physics and the Universe

The Universe We Live In
Cosmology: Past, Present, Future

Big Bang



Hubble

Black Holes

Hawking

Announcements

- **Schedule:**
  - **Today:** Current Physics - The Universe
    March (parts of Ch. 12 , 20)

    Report/Essay Due Today

  - **Next Time:** Summary of Course

- **Final Exam** **Friday, Dec. 19, 7-10 PM**
  Room 151 Loomis

Additional Information

- **References**
  - Sir Martin Rees, "Before the Beginning"
  - Steven Weinberg, "The first three minutes"
  - Steven Hawking, "A brief History of Time"
- **Web Sites (Others on Links on class WWW pages)**
  - General Science Sites:
    - http://www.pbs.org/science/ http://www.wnet.org/
  - Many excellent Web Sites on Astronomy. Ones I have used are:
    - Images of Galaxies with explanations
      http://csep10.phys.utk.edu/guidry/violence/galaxies info.html
    - PBS Web site to accompany 1997 Hawking Series
      http://www.pbs.org/wnet/hawking/html/
    - The Electronic Universe Project
      http://zebu.uoregon.edu/
    - NASA WEB page http://www.nasa.gov/
    - "Best of Hubble" http://www.seds.org/hst/hst.html
    - Hubble Heritage Project http://heritage.stsci.edu/

Introduction

- **Where are we now in understanding of physics**
  - Newton's Laws describe motion of matter EXCEPT
    - Quantum Mechanics needed for the very small
    - Special Relativity needed for speeds near c
    - General Relativity needed for strong gravitational fields
- **Our Universe**
  - What do we see with the naked eye?
    - Sun, Moon, Planets, Stars (in our galaxy), Supernovae
  - What do we see with optical telescopes, other instruments?
    - Other Galaxies, Pulsars, ……..
  - Objects in our universe
    - Stars, Collapsed Neutron Stars (pulsars), Black Holes, ...
  - Cosmology
    - Evidence for the "Big Bang"
    - Will the Universe keep expanding, collapse in the "Big Crunch" , or slow to a stop?

Galaxies

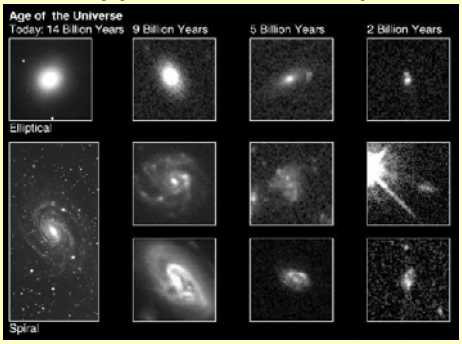
- **Our sun is a small star toward the outside of the galaxy, the Milky Way (a spiral galaxy) containing approximately 200,000,000,000 stars (2 x 10^{11})**
- **A few others (e.g. Andromeda) visible to naked eye**
- **Telescopes reveal many galaxies, each ~ 10^{11} stars**

Andromeda

Spiral Galaxy m100

Different types of Galaxies

- **The furthest are the oldest - what we see is light from the early period of the universe (more later)**



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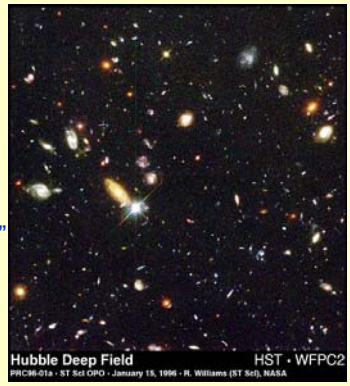
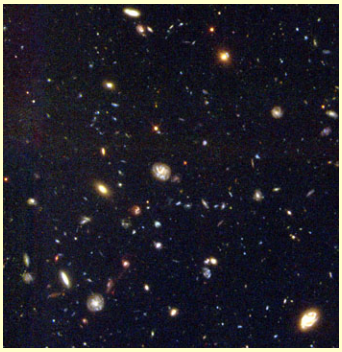
Views from the Hubble Telescope

- Picture of an area of the sky (the size of a grain of sand held at arm's length) in which there are no stars visible to the naked eye!
- Shows visible stars in the Milky Way and distant "fuzzy looking" galaxies
- Some of the objects seen are among the oldest known objects



Views from the Hubble Telescope

- Picture of part of southern sky released Nov. 23, 1998
- You can see the "red shifted galaxies" by their color - they are moving away from us at speeds a large fraction of c
- Some are "red shifted" so much the light is not visible to our eyes - seen only in infrared. These are the oldest objects known

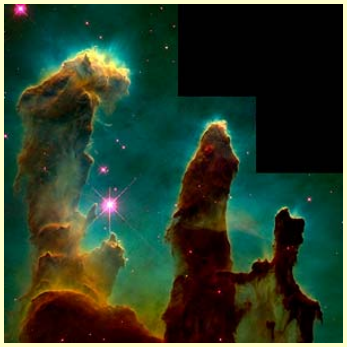


The Life of Stars and Galaxies

- Galaxies form from clouds of gasses (mainly hydrogen) pulled together by gravity
  - How do we know what galaxies stars are made of?
  - Atomic spectral lines! Just like here on earth!
- Stars form from condensation of gasses within a galaxy due to the pull of gravity
  - Start to "burn" nuclear fuel when they become so dense and hot that nuclei fuse and release energy
  - Our sun is fueled by burning hydrogen (proton) and deuterium (proton + neutron) to form helium nuclei
  - Other elements formed in larger stars and the heavy elements are formed in a Supernova ! (More later)
  - We are the remnants of supernovae !

The Birth of a Star

Image from the Hubble Telescope showing formation of stars from clouds of hydrogen gas



The end of the life of a star

- What happens when the nuclear fuel runs out?
  - The star collapses because of the pull of gravity
- Its fate depends upon its mass
  - Very small stars (less than our sun) become brown dwarfs like giant Jupiters
  - Small stars (like our sun) become white dwarfs collapsing to a size similar to that of the earth
  - Large stars collapse to Neutron Stars or Black Holes
    - Collapse causes a Supernova! Release of more energy than a galaxy from one star for a short time (months)
    - For mass > 1.3 mass of our sun, becomes a Neutron Star -- Observed as Pulsars
    - For mass > 1.5 mass of our sun, becomes a Black Hole Pull of Gravity so strong that nothing can escape!

Remnant of a Star that has Exploded

- Clouds of gasses ejected from central star - smaller than our sun. It is now very hot and will cool to a white dwarf

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Supernova

- Expels matter - all heavy elements in the universe (in you!) are formed in supernovae
- Remnant is a neutron star or black hole
- Radiates more energy than an entire galaxy for a brief period (months):
  - Famous supernovae:
    - 0 -- The Christmas Star ??
    - 1054 -- in Crab Nebula, Recorded in China, …..
    - 1572 -- in large Magellanic Cloud, seen by Kepler
    - Pulsars (Neutron Stars) observed now as remnants of the 1054 and 1572 Supernovae!
    - 1987 -- in Magellanic Cloud - remnants still observed

The Strange Objects in our Universe

- Quotations from Prof. Fred Lamb, UIUC Depts. Of Physics and Astronomy
- There are objects in our universe that are:
- More massive than our sun
- About the size of Champaign-Urbana
- Rotating at thousands of times per second
- Radiating milions of times more energy than our sun (mainly x-rays)
- Most of the radiation comes from a "hot spot" about the size of the UIUC campus

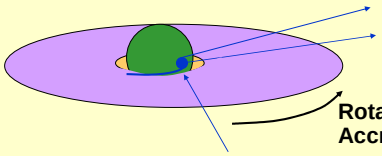
Neutron Star

- Proposed in 1928 by S. Chandrashekar
  - Star collapses under gravity to such a density that electrons and protons combine to form Neutrons!
  - Like one giant nucleus!
  - Extremely dense: Mass > our sun in a sphere of radius a few km!
  - Observed as "Pulsars"
  - Discovered by Radio Telescopes in England in 1967
  - Graduate Student Jocelyn Bell observed very strong radio signals from certain galaxies. Pulse at rates of thousands of pulses per second! Extremely regular!
  - Interpreted as very small neutron stars rotating at thousands of rotations per second !

Radio Waves are our main way to observe Pulsars

What "feeds" a small massive object

- An Accretion Disk of gasses that are sucked into the massive object by gravity (Like Rings of Saturn)
- Often from a nearby star



Rotation of Accretion Disk

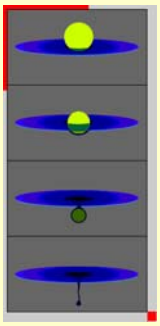
Matter spiraling into "hot spot"

Crab Pulsar – the size of Manhattan

- Image from Hubble Telescope
- http://oposite.stsci.edu/pubinfo/PR/2002/24/

Black Hole

- Idea First Proposed in 1783 by John Mitchel
- Modern Name "Black Hole" invented by John Wheeler in 1952
  - Idea follows from Einstein's General Relativity
  - Space time is curved in the presence of matter
  - If there is enough mass, one solution of equations is a singularity: Spacetime is curved on itself to form a "Black Hole"
  - A Black Hole means that the effects of gravity are so strong that nothing, not even light, can escape
  - If an object falls toward a black hole, time slows down until it ceases at the "edge" of the black hole



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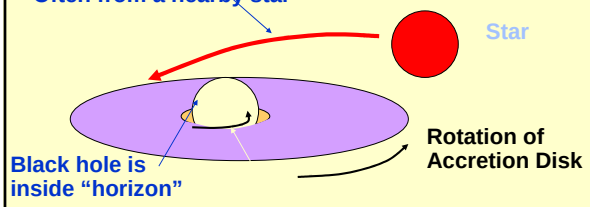
What is it like near a black hole?

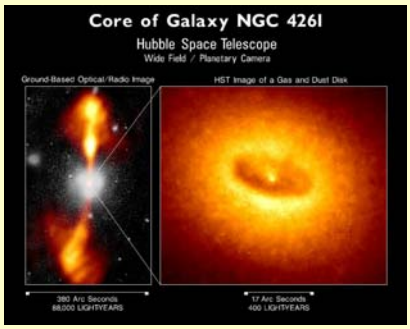
- An Accretion Disk of gasses forms like that for a neutron star -- sucked into the massive object by gravity
- Often from a nearby star



Matter spiraling into Black Hole disappears beyond the "Horizon" from which no light can escape

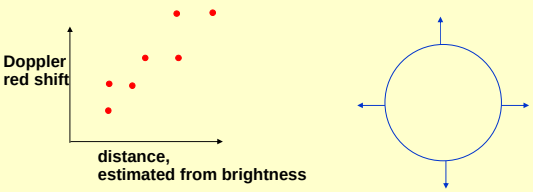
Image of a black hole?

- Image of the accretion disk of gasses – evidence enormous massive object in the center of this region



Hubble and the Expanding Universe

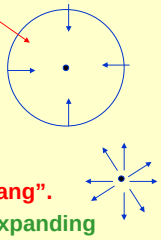
- In 1929, American astronomer Edwin Hubble announced the discovery that galaxies appear to be moving away from us in all directions!
- Light from distant (faint) stars is "Doppler shifted toward low frequencies"- they seem to be receding from us.



- How can universe appear to expand in all directions?
  Does this mean we are at the center? NO!

Big Bang

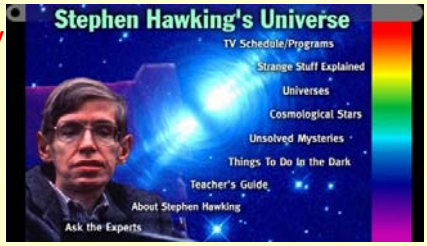
- Follow velocities backward about 15 billion years
  - (More recent value than 12 billion years which is stated in text)
- The universe was all at the same place!
- Taking into account general relativity (gravity), it implies the universe was condensed into an infinitely dense point.



- That moment is called "The Big Bang".
- Since then space-time has been expanding
  - Objects are NOT flying away from a 'center".
  - Every object is an equally good center.
  - There is no edge! Space-time itself is finite!

The Big Bang and Black Holes?

- In 1960 Stephen Hawking showed that if the universe is expanding then there must have been a singularity at the beginning



- In 1974 he found that black holes are not really black! Quantum Mechanics says particles, antiparticles are created at the boundary, which radiates energy!

What happened after the Big Bang?

- Current theory (e.g. Weinberg, "The first three minutes")
- Evolution is proposed to be a series of steps, where particles "freeze out" and matter condenses into different forms
  - Analogy: Start with very hot H and O atoms. As the temperature is lowered the atoms form H_2O molecules, then molecules condense to steam droplets, then water, then ice.
- First Moments after Big Bang: Very Hot, $T > 10^{12}$ K
  - Free Quark- Gluon- Electron- Neutrino - photon plasma
- ~0.1 sec later: $T \sim 10^{11}$ K
  - Quarks, Gluons "freeze out" to form neutrons and protons
- ~10 sec later: $T \sim 3 \times 10^{9}$ K
  - Nuclei like He begin to form
- ~3 min later: $T \sim 10^{9}$ K
  - Deuterium can form - (~ 70 times hotter than center of our sun)

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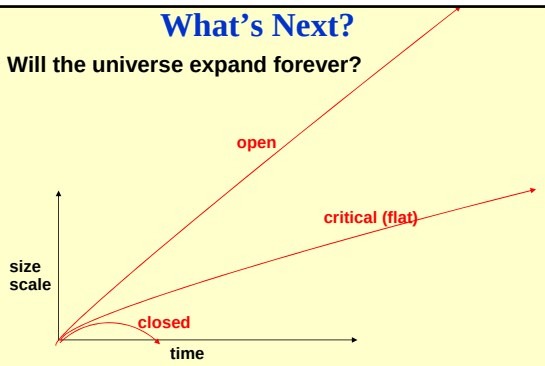
What happened after the Big Bang?

- ~700,000 years later: T ~ 10^4 K
  - Neutral atoms can form by electrons binding to nuclei
  - Photons "freed" because they do not interact strongly with neutral atoms
- Universe continues to cool until now
  - Galaxies, stars, planets, ... form
- The radiation (photons) cool and is now observed as the "3 degree background"
  - Observed at Bell Labs in 1964 as "extra noise" in antennas
  - Interpreted as radiation pervading all space about the same in all directions
  - Not due to galaxies or stars
  - A remnant of BIG BANG! The radiation which has cooled to the present temperature of 3 K

What's Next?

- Will the universe expand forever?



Future scenarios

- Open: everything gradually runs down in a dilute cold future
- Critical: same as in open, except space-time becomes flat on large scale
- Closed: everything collapses back to a hot "big crunch"
- How can the "big crunch" happen?
  - If there is enough mass gravity can pull things together again!
  - Note: It is not that the universe collapses in a fixed space. Gravity pulls space itself together.

Which fate?

- The key factor is the mass density, ρ.
  - The critical density is given by ρ_c - 1/G (15 billion years)^2
- If $\rho > \rho_c$ then the universe will stop expanding and collapse to the "big crunch"
- If $\rho < \rho_c$ then the universe will expand forever
- What is the answer?
  - Mass of visible stars: $\rho < 0.1\ \rho_c$
  - Other mass? Evidence for other mass but at present estimates are $\rho \sim < 0.3\ \rho_c$
  - We do not know the answer!
  - Is there a missing mass? More ordinary mass? Some exoctic mass?

How do we detect mass that is not visible?

- Matter orbiting the outer parts of galaxies shows there is mass not included in the stars
  - See motion by "blue" and "red" shifts of spectral lines

- How can we find Mass of the Galaxy? (Exercise)
- Work of Vera Rubin (Student of George Gamov) in the 1960's
- Concludes there must be a "halo" of mass. What is it??

Exercise

- Exercise: How can we use knowledge of velocities to find the mass of the galaxy including any mass not visible?
  - Observe light from objects well outside the visible galaxy

- Assuming all the mass is in the visible part of the galaxy, should the velocity decrease or increase as a function of the distance R of the objects from the center?
- How should it vary as a function of the distance R?

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Exercise

- **Exercise: How can we use knowledge of velocities to find the mass of the galaxy?**

- This is the same as Kepler's 3rd law, which can be derived from Newton's laws:
- $F = ma = G\,mM/R^2$; So $a = G\,M/R^2$;
- Also $a = v^2/R$, so $v^2 = G\,M/R$
- Assuming the mass does not change with R, i.e., all the mass is well inside the radii R being considered, then the velocity can be used to find the mass, and the velocity is expected to decrease as 1/sqrt(R)

What actually happens

- **This is not what is found experimentally!**
- **(Vera Rubin, 1960's)**

- **The velocity stays roughly constant and does not decreases with 1/sqrt(R)**
- **Implies there is extra mass in a halo around the galaxy, more than the visible mass!**
- **What could it be? Jupiter-like objects, gasses, other?**

How do we detect mass that is not visible?

- **Galaxies form clusters that show gravitational effects of matter in addition to the visible stars**
- **Other observations show presence of matter**

False color picture of x-rays from matter outside a galaxy

Cluster of galaxies in Virgo Constellation

Questions - Answers not known

- **What will be the fate of the universe?**
  - **Is there "missing mass"? What kind?**
- **How did the universe form?**
  - **This is the question of cosmology which leads us to quantum mechanics and elementary particles**
- **How did large scale structures form?**
  - **Does observation of clusters of galaxies and small differences in "3 degree background" tell us something about the "Big Bang" and origin of the universe**
- **What actually is the nature of black holes?**
  - **What happens at the boundary of black holes**
  - **How do they affect their neighbors?**
- **Is there a black hole at the center of our galaxy?**

Summary I

- **The Universe around us**
  - **Our sun and solar system is a small part of the Milky Way**
  - **Milky Way: A spiral galaxy of ~ 200,000,000,000 stars (2×10^{11})**
  - **Almost all the stars we see are in the Milky Way**
  - **Billions and billions of other galaxies visible with telescopes**
- **Galaxies and stars form from gases (mainly H) pulled together by gravity**
  - **Stars produce energy from Nuclear fuel**
- **Death of a star**
  - **Supernova! Release more energy than a galaxy (for months) All heavy elements formed in supernova!**
  - **Remnant of Collapse:**
  - **Small stars becomes brown dwarfs**
  - **Larger (like our sun) become white dwarfs**
  - **Mass > 1.3 sum mass: neutron star (pulsar)**
  - **Mass > 1.5 sun mass: black hole**

Summary II

- **Strange Objects in our Universe**
- **Neutron Stars - like a giant nucleus**
  - **Form "Pulsars"**
  - **Very small - mass of sun in radius like Champaign Urbana**
  - **Rotate thousands of times per second**
  - **Radiate millions of times more energy than the sun from a "hot spot"**
- **Black Holes**
  - **Matter that collapses upon itself**
  - **So much mass that space time curves on itself- nothing can escape**
  - **Consumes gasses from nearby stars**
- **Invisible Mass**
  - **What is it?**
  - **How do we detect it?**
  - **From the motions of visible objects and the laws of physics!**

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Summary III

- The Universe is Expanding
  - Found by Hubble in 1927 29
  - Measured by "Doppler Shift"
  - Expanding in all directions as if it came from a point
  - Estimate for age of universe ~ 15 billion years
  - Compare to estimate of age of the earth ~ 5 billion years
- The BIG BANG
  - Evidence is the expanding universe
  - The "Cosmic Background" of radiation observed (1964)
  - "3 degree background" remnant of BIG BANG
- Future?
  - A. Universe keeps expanding (becomes cold and empty)
  - B. Expansion slows to a stop (becomes cold and dead)
  - C. Reverses and collapses to the BIG CRUNCH
  - Depends upon the total mass
  - We do not know the mass well enough to know the answer!