Astronomy 162, Week 10
Cosmology

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Information

- Makeup quiz Wednesday, May 31, 5-6PM, Planetarium
- Review Session, Monday, June 5 6PM, Planetarium

Cosmology

- Study of the universe as a whole
- In 1950s, it was metaphysics as much as science
- Now - a very active & developed field of both
  - observational astronomy
  - theoretical astrophysics
  - (OSU has a very strong program in cosmology)

Fundamental questions

- How large is the universe?
- How far can we see?
- How did it begin? Or, at least
- When did it begin?
- What happened afterward?
- What will happen in the future?
- How did current structures (galaxies, etc) form?
- How were the elements formed?

Expansion of the Universe

- Recall the Hubble law
  - it is same in all directions
  - two consequences become two principles
  - Copernican principle - we are not at center of expansion
  - Cosmological principle - isotropy and homogeneity mean universe looks the same from any place

Fig. 28-3, Expanding Universe

- Does the universe look same at all times?
  - If it did, that would be the perfect cosmological principle (which led to the steady state universe)
  - But current observations show it did not look the same at all times (e.g., more quasars in the past)
  - Thus, the Big Bang model is favored

Will expansion continue forever?

- What can slow the expansion?
  - Gravity
- What determines the strength of the gravity?
  - The density of mass in the universe
  - Denoted by symbol Ω_M

Outline of Discussion

- We will first consider the effects of gravity, as we have discussed it so far, on the expansion of the universe
  - This provides a framework for considering the curvature of spacetime
  - Then, at the end of the discussion, we will consider the amazing implications of dark energy and the accelerating universe

Consider three possibilities

- Mass density is low (Ω_M<1). Then universe is open, expansion continues forever
- Mass density is high (Ω_M>1). Universe is closed. Expansion will stop at some time, then universe will start to contract
- Mass density is just enough to stop expansion at infinite time (Ω_M=1). Universe is flat.

Curvature of space-time

- Recall that gravity bends light
- There is a relation between mass density in universe and the curvature of space
  - High mass - positive curvature, closed universe
  - Low mass - negative curvature, open universe
  - Critical mass - curvature is flat

– See Table 28-1

Fig. 28-15, The Geometry of the Universe

Age of universe

- Matter in universe slows expansion
- Age must be less than Hubble time (if no other forces acting)
- If space is flat, age of universe is 2/3 of Hubble time, or about 10 billion yrs
  - Need to know density of universe to determine age, eventual fate, and curvature

Lookback time

- Time it takes light to arrive from distant object
  - depends on density of universe (curvature of space)

Concept of horizon

- If universe had a beginning (the big bang)
- then there is a limit to how far we can see
  - namely, the age of the universe times the speed of light
  - that distance is the horizon distance
  - universe can still be infinite, but we can't see beyond horizon

Fig.28-5, The Observable Universe

Observational tests

- We need to determine the mass density in the universe to know its ultimate fate
  - also how the expansion rate changes with time
- There is a tremendous effort to identify all the galaxies and the dark matter
  - they determine the density
  - critical density is that required to just stop the expansion at infinite time

- So far, the density of everything measured (matter and dark matter) in the universe is less than the critical density (Ω_M<1)
  - this would favor the expansion continuing forever
  - (The latest results indicate that the universe is accelerating, due to dark energy)

Why is the sky dark at night?

- Often called Olber's paradox.
  - If the universe is infinite,
  - every line of sight should eventually reach a star
  - the sky should be as bright as the surface of stars
  - which it obviously is not
  - Why isn't the sky bright?

- Possible causes of the dark sky
  - cosmological redshift dims the light of stars
  - dust
  - both could be factors, but
  - the main reasons are:
  - the universe had a beginning
  - stars were born after the beginning
  - the horizon limits how far we can see

- Also, there isn't enough mass density in the universe to produce enough stars
- Thus, the seemingly trivial observation that the sky is dark at night, an observation we make without telescopes,
- has profound consequences - the universe had a beginning and a limited mass density

What was the universe like in the beginning?

- Think about going back in time.
  - Universe was smaller, objects were closer together, density was higher
  - temperature must have been higher
  - If we push concept to its limit, we see that
  - the universe began i
  - n a hot, dense, rapidly expanding state
  - The Big Bang

Astronomy 162, Week 10
Cosmology, continued

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Cosmic Background Radiation

- How far back can we see?
  - Until universe is opaque, not farther
  - Temperature was about 3000 deg then
  - What is it now?
  - Temp. drops as $1/(1 + z)$, z is redshift
  - Temp. of universe now about 3 deg
  - Idea first realized by Gamow, Alpher, Herman in 1940s, but not then observable

- In 1960s, Robert Dicke had same idea, worked with Peebles, Roll, Wilkinson
- Meantime, Penzias and Wilson, Bell Labs, discovered mysterious signal with communications antenna (1965)
  - they detected the faint echo of the big bang
  - received Nobel Prize

Fig. 28-6, Bell Labs Horn Antenna

- Discovery of the background radiation confirmed the big bang hypothesis
  - Radiation is observed to be uniform in all parts of the sky

- Spectrum is a perfect black body for temperature of 2.7 deg (absolute) (Fig. 28-7)
- Radiation is observable only in microwave and far IR region, not at visible wavelengths

- Improved data show slightly hotter temperature in one direction of sky, cooler in opposite direction
  - indication of our motion through the universe
  - our Local Group is moving in direction of Centaurus
  - Is there a Great Attractor? (that is, a great concentration of mass)

Structure Formation

- Can we explain
  - Why background radiation is so smooth
  - But present universe is so clumpy (galaxies, clusters of galaxies, superclusters, Great Wall)
  - How, when did structure develop
  - General idea, slight fluctuations in early universe get amplified by gravity

COBE

- Cosmic Background Explorer
  - satellite designed to observe background radiation (Fig. 28-7)
  - 1992 - announced discovery of slight irregularities in radiation
  - irregularities that would later form into large structures, eventually into galaxies

Fig. 28-7a, The Cosmic Background Explorer

Current work

- New satellites and ground-based work are detecting the fluctuations on much smaller scales, determine the nature of the early universe

The Early Universe

- If we continue extrapolating backwards in time toward the Big Bang,
  - we'll find the universe to be hotter and denser
  - we'll reach the limit of what we know about physics
  - consider the main concept -
  - the universe began in a giant, primeval, exploding fireball

- If the universe began in a hot dense, state, can we understand
  - the origin of the elements?
  - the origin of structure in the universe?

After the Big Bang

- At the earliest times, universe was so hot, only subnuclear particles, interacting with radiation, could exist
  - there were no elements as we know them
  - situation was not like the interior of a star

- Let's start our discussion at a time of 0.01 sec, temperature of 100 billion deg
  - there is a slight excess of matter over antimatter
  - protons, neutrons can exist
  - collision of photons creates electrons, positrons
  - huge number of neutrinos emerge
  - As time progresses, universe cools, density drops

- There are two key results
  - more protons left than neutrons, thus hydrogen is the most abundant element in the universe
  - helium is also produced, in about the amount observed today (deuterium is left as a signature)
  - work at OSU by Steigman, Walker
  - this is the state at the end of the first 4 minutes

- (see book “The First Three Minutes” by S. Weinberg - summer reading)
- Universe like interior of star
  - hot
  - opaque
  - but no significant nuclear reactions going on
  - heavier elements are later produced in stars, as we have already studied

What happens next?

- Universe continues to expand, cool
  - it’s also opaque, because H, He are ionized
- After about 380,000 yrs, H, He, recombine into atoms
  - universe becomes transparent
  - radiation, matter start to evolve separately
  - cosmic background radiation we now see is from recombination era

Questions about Big Bang

- Why does the universe appear so uniform?
  - regions on opposite parts of sky not in contact (outside horizon)
- Why is the density near the critical value?

Inflation

- Answers involve
  - grand unified theories of physics
  - the extreme conditions in the early universe (10^{-35} sec)
  - concept of phase transition led to rapid expansion (inflation) of universe
  - the (now) observable universe was inside the horizon before inflation, in equilibrium

  - after inflation
  - the regions separate, evolve independently
  - inflation will produce density equal to critical value
  - inflation also consistent with much dark matter in universe
  - but it’s probably not the whole story

Formation of structure

- Current work on the formation of large scale structure
  - starts with the small fluctuations that must have existed in the early universe
  - includes the physical processes like gravity that should be important
  - develops models of how large scale structure and galaxies formed

What is the Fate of the Universe?

- Current best guess is that it will expand forever?
- Stars will eventually die out

What about the Accelerating Universe?

- Distant supernovae are observed to be slightly too faint
  - Evidence for an accelerating universe – some force acting against the pull of gravity (Figs. 28-17, 28-18)
- Latest data on the microwave background indicate universe is flat
  - BOOMERANG map, Fig. 28-16

- Results from Hubble Space Telescope on distant supernovae. See
  - http://hubblesite.org/newscenter/newsdesk/archive/releases/2004/12/

- Best current interpretation of supernova data is that the universe is consistent with a cosmological constant

Fig. 28-18, Hubble Diagram for Supernovae
The BOOMERANG launch
Fig. 28-16, Boomerang Map of Microwave Background and the Curvature of Space

What does this mean?

- Some form of dark energy is needed to
  - provide the acceleration, and
  - give the universe a flat geometry
- The nature of the dark matter and the nature of the dark energy are perhaps the two greatest mysteries in astronomy and physics today

Einstein and the Cosmological Constant

- General Relativity
  - Equations imply universe should expand or contract but not be static
  - Einstein introduced the cosmological universe to yield a static solution
  - Later called this the biggest blunder of his life
  - Now, the supernova data indicate there is such a constant

Recent Results in Cosmology

- WMAP – astounding new information on the universe 380,000 yrs after Big Bang
  - Gives information on geometry (flatness) of universe, age, dark energy …

WMAP Misison

- Wilkinson Microwave Anisotropy Probe
  - See the excellent web site at http://map.gsfc.nasa.gov/index.html

Fig. 28-14, WMAP Full Sky Image
COBE – WMAP Comparison

Stay tuned

- There will be many new results on these topics in the next few years