Astro 2299

The Search for Life in the Universe
Lecture 4

This time:

• Redshifts and the Hubble Law
• Hubble law and the expanding universe
• The cosmic microwave background (CMB)
• The elements and the periodic table

Assignment 1 on course web page (due 15 Feb)

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http://www.astro.cornell.edu/academics/courses/astro2299/
Main points from last lecture

• Galaxies differ and evolve
• Giant black holes are at the centers of quasars (= quasi-stellar objects) and evolve with galaxies
• The darkness of the night sky is a consequence of the finite age of the universe
• The universe appears to be homogeneous and isotropic (if you squint)
• Redshifts are a fundamental tool in cosmology and result from kinematic (doppler) motion and from gravitational redshifts
The Cosmic Web

Viewed on a scale of about 0.3 Gpc

Image credit: John Dubinski (U of Toronto)

Caption: The Cosmic Web. This is a slice from a simulation of a cold dark matter model of the universe representing a patch about 1 billion light years across. Here we "see" the dark matter in blue a few billion years after the Big Bang. Small noisy fluctuations in the density of matter grow via gravitational instability as the universe expands and evolve into the cosmic web we see here. At the intersection of filaments, the matter collapses into dense blobs known as dark matter halos and become the birth places of the galaxies.
The Laniakea Supercluster of Galaxies
Cosmological wavelength shifts are not only from the Doppler effect!

\[ z = \frac{\lambda - \lambda_0}{\lambda_0} \]

\( \lambda_0 \) = rest (laboratory) wavelength

- Redshift means the shift of spectral lines redward, i.e. to longer wavelengths

- Physically redshifts occur in three ways
  1. The source of light is moving away from an observer (kinematic redshift)
  2. The source of light is in a gravitational well so that light has to work against gravity to get to the observer (gravitational redshift)
  3. The source of light is at some cosmological distance (cosmological redshift)
    - This effect is a combination of 1 and 2 + expansion of spacetime
    - It is not correct to think of galaxy redshifts as measuring only “recession velocities”
Gravitational Redshift

• Light from an atom in a potential well will appear at a longer wavelength than $\lambda_0$ to an observer outside the potential well.

• For shallow wells $z_g = GM/rc^2 << 1$.

• The gravitational redshift was measured in a Harvard lab in the early 1950s and has been measured from atoms in white-dwarf atmospheres and in many other astronomical contexts. [https://en.wikipedia.org/wiki/Gravitational_redshift](https://en.wikipedia.org/wiki/Gravitational_redshift)

• Important for GPS = global positioning system! ‘Relativity in the Global Positioning System,’ Ashby
Relativity in the Global Positioning System

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Abstract

The Global Positioning System (GPS) uses accurate, stable atomic clocks in satellites and on the ground to provide world-wide position and time determination. These clocks have gravitational and motional frequency shifts which are so large that, without carefully accounting for numerous relativistic effects, the system would not work. This paper discusses the conceptual basis, founded on special and general relativity, for navigation using GPS. Relativistic principles and effects which must be considered include the constancy of the speed of light, the equivalence principle, the Sagnac effect, time dilation, gravitational frequency shifts, and relativity of synchronization. Experimental tests of relativity obtained with a GPS receiver aboard the TOPEX/POSEIDON satellite will be discussed. Recently frequency jumps arising from satellite orbit adjustments have been identified as relativistic effects. These will be explained and some interesting applications of GPS will be discussed.
Hubble Law

Hubble showed (1920s) that galaxies motion trended away from us faster the more distant:

\[ c \, z = H_0 \, d \]

- \( c \) = speed of light
- \( z \) = redshift
- \( d \) = distance
- \( H_0 \) = Hubble ‘constant’

For \( cz \) in km/s and \( d \) in Mpc, \( H_0 \) is in km/s/Mpc

Current best estimate: \( H_0 \sim 70 \) km/s/Mpc
Meaning: galaxies at 100 Mpc distance will, on average, be moving about 7000 km/s away from us.

Most galaxies in fact appear to be moving away from us.

Exception: Andromeda (M31) is moving toward us because M31 and the MW are gravitationally bound to each other; eventually we will merge.

Can have \(cz > c\) = speed of light because redshifts \(z\) have been measured for galaxies and AGNs as large as \(~9.5\).
Spectra and spectral lines from galaxies
Edwin Hubble’s original data (1920s)

Velocity-Distance Relation among Extra-Galactic Nebulae.
Radial velocities, corrected for solar motion, are plotted against distances estimated from involved stars and mean luminosities of nebulae in a cluster. The black discs and full line represent the solution for solar motion using the nebulae individually; the circles and broken line represent the solution combining the nebulae into groups; the cross represents the mean velocity corresponding to the mean distance of 22 nebulae whose distances could not be estimated individually.
Mass-energy determines geometry

Geometry determines where mass-energy can go
Critical Mass Density for the Universe

We can get an estimate of how much mass is needed to “close” the universe. More accurately, we calculate the mean density needed to close the universe.

We balance gravitational potential energy and kinetic energy using simple Newtonian mechanics.

Potential energy of mass $m$ in gravitational field of $M$

$$PE = -\frac{GMm}{R}$$

Kinetic energy of mass $m$

$$KE = \frac{1}{2}mV^2$$

Total energy:

$$E = KE + PE = \frac{1}{2}mV^2 - \frac{GMm}{R}$$

Total energy: $E = 0$ corresponds to mass $m$ having escape velocity from $M$

$$V_{esc} = \left(\frac{2GM}{R}\right)^{1/2}$$

Example: Earth

$R \sim 6371$ km
$M = 5.97 \times 10^{24}$ kg

$V_{esc} \sim 11.2$ km/s
Critical Mass Density for the Universe II

We can get an estimate of how much mass is needed to “close” the universe. More accurately, we calculate the mean density needed to close the universe.

We balance gravitational potential energy and kinetic energy using simple Newtonian mechanics.

\[ E = 0 \] corresponds to mass \( m \) having escape velocity from \( M \)

\[ E = KE + PE = \frac{1}{2} mV^2 - \frac{GMm}{R} \]

We can also solve for \( E = 0 \) from

\[ \frac{M}{R} = \frac{V^2}{2G} \]

Now we consider \( m \) to be any object in the universe and we relate its velocity to the Hubble law, \( V = H_0 R \)

Then:

\[ \frac{M}{R} = \frac{V^2}{2G} = \frac{(H_0 R)^2}{2G} \]

Or:

\[ \frac{M}{R^3} = \frac{H_0^2}{2G} \]

\[ \frac{M}{(4\pi/3)R^3} = \frac{H_0^2}{2G(4\pi/3)} = \frac{3H_0^2}{8\pi G} \]

This gives a mass density \( \rho_c \)

\[ \rho_c = \frac{3H_0^2}{8\pi G} \]

Critical mass density \(~ 10^{-29} \text{ g cm}^{-3} \)
Critical Mass Density for the Universe III

\[ \rho_c = \frac{3H_0^2}{8\pi G} \]

Critical mass density \( \sim 10^{-29} \text{ g cm}^{-3} \)

Densities:
- H atom \( m_H \sim 10^{-24} \text{ g} \)
- \( n_c = \rho_c / m_H \sim 10^{-5} \text{ atoms/cm}^3 \)
- Water: \( 10^{23} \text{ atoms/cm}^3 \)
- Interstellar gas: \( \sim 0.01 \text{ atoms/cm}^3 \)
- Neutron star: \( \sim 10^{14} \text{ g/cm}^3 \)

We used a simplistic approach to derive \( \rho_c \): Newtonian mechanics and treating the recession velocity from the Hubble law as an actual velocity.

Using General Relativity, the same answer is gotten!

Utility:

We can express all constituents in the universe relative to \( \rho_c \)

For example if the mean matter density is \( \rho_m \) then it can be expressed as

\[ \Omega_m = \frac{\rho_m}{\rho_c} \]

If \( \Omega_m > 0 \), enough matter would exist to halt the expansion of the universe

For many years, people tried to identify matter in the universe to determine if the universe is open or closed. Along the way, dark matter was identified. Then dark energy. The universe does not appear to be closed.
Type Ia Supernovae

SN 1994D
Astronomy Picture of the Day
Science's Breakthrough of the Year: The Accelerating Universe
Density = Destiny

Because

the theme for many processes is Gravity vs. kinetic energy

(the universe, formation of galaxy clusters and galaxies, stars, planetary systems)
Density = Destiny

Old picture:
The universe is open or closed depending on whether gravity loses or wins against kinetic motion, including pressure
How the universe works

Density = Destiny

New picture:

The universe is open and its expansion is accelerating. As time goes on and on, our horizon decreases in size: we will see less and less of our surroundings.

Density of what: all mass-energy distorts space-time so gravity is due to everything, not just masses (e.g. photons count too, though massless).
Brief History of time

- **INFLATION**
- **CMB** (Cosmic Microwave Background)
- last scattering
- fraction of a second
- 379,000 years
- present day
- first stars
- ~200 million years
- 13.7 billion years
Discovery of Cosmic Background

Microwave Receiver

Robert Wilson

Arno Penzias
Figure 2. Terrestrial microwave window.
Color code: green = 2.7K.

Temperature is highly uniform across the whole sky.

Constant 2.7K subtracted; yin-yang pattern = “dipole” due to our motion relative to rest frame of the CMB ... a Doppler effect.

Dipole subtracted revealing Galactic plane and temperature fluctuations in the CMB ~ $10^{-5}$ K.
This is where we're coming from...

March 11th

Virgo

Sept. 10th
ecliptic

...and this is where we're going to...

CMB Dipole

371 km/s
830,000 mph

-3354 uK_CMB
3354 uK_CMB