The Expanding Universe

Relativity and Astrophysics
Lecture 18
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Outline

- Age of the Universe
- The Big Bang
- Useful table
  - Look-back times and distances vs. redshift
The Age of the Universe

- Hubble’s law tells us that for galaxies: \( v = H_0 d \)
- Since the universe is expanding, galaxies were closer together in the past.
- Extrapolating backwards, all the galaxies were on top of one another! – When was this?

Age (cont’d)

- If the universe has been expanding uniformly, the time for this is:
  \[ t = \frac{d}{v} \]
- Inserting Hubble’s law:
  \[ t = \frac{d}{H_0 d} = \frac{1}{H_0} \]
- Suppose \( H_0 = 100 \text{ km/sec/Mpc} \), then
  \[ t = \frac{1}{H_0} = \frac{1 \text{ sec}}{100 \text{ km}} \frac{1 \text{ yr}}{3 \times 10^7 \text{ sec}} \frac{10^6 \text{ pc}}{3 \times 10^{15} \text{ km}} = 10^{10} \text{ yr} \]
- So
  - for \( H_0 = 100 \), \( t = 10 \times 10^9 \text{ years} = 10 \text{ billion years} \)
  - for \( H_0 = 50 \), \( t = 20 \times 10^9 \text{ years} = 20 \text{ billion years} \)
  - for \( H_0 = 71 \), \( t = 14 \times 10^9 \text{ years} = 14 \text{ billion years} \)
The Expanding Universe

Historical Measurements of $H_0$

The Big Bang

- The present location and velocities of galaxies are a result of a primordial blast known as the **BIG BANG**.
  - THE BEGINNING OF THE UNIVERSE
  - THE BEGINNING OF TIME?!

- What is the BIG BANG?
  - The Big Bang was NOT an explosion in an otherwise empty universe.
  - The Big Bang involved the entire universe.
  - At the beginning the Big Bang happened everywhere at once.
Expansion of the Universe

- As the Universe expands
  - Galaxies move further apart
  - Photons “stretch” (get redshifted)
- The 2-D analog is an expanding sphere
- Thus the cosmological redshift we see is due the expansion of space itself.

Source Flux: Cosmological Effects

- Effects of redshift on flux – compared to emission in rest frame
  - Photons lose energy
  - Time dilation so photons come out at a slower rate
  - Filter bandwidth maps to different width
- Geometric effect
  - Hidden in $a^2$ term for the flux.

Example: $z = 1$ at source

Astronomer uses a filter operating from 4 and 5 GHz. The photons were emitted from the source with frequencies 8 and 10 GHz.

$$4 \cdot (1 + z) - 4 \cdot (1 + 1) = 8$$
$$5 \cdot (1 + z) - 5 \cdot (1 + 1) = 10$$

blue = emitted
red = observed (dashed)
Look back times

- As we look further out in the universe we are seeing it at earlier times!
  - It takes a long time for light to get here.
- Telescopes are thus “time machines” which allow us to look at the early universe.

- The following table shows the “look-back” time as well as
  - Luminosity distance = effective distance to convert flux into luminosity
  - Angular diameter distance = effective distance to get the size of an object as seen from the Earth

<table>
<thead>
<tr>
<th>redshift</th>
<th>v/c</th>
<th>Look-back time</th>
<th>Time after Big Bang</th>
<th>Luminosity distance</th>
<th>Angular diameter distance</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>(Gyr)</td>
<td>(Gyr)</td>
<td>(Glyr)</td>
<td>(Glyr)</td>
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<tr>
<td>0.1</td>
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</table>

Calculations for $H_0=71$ km/sec/Mpc, $\Omega_m = 0.27$, $\Omega_{\Lambda} = 0.73$. For an observed flux, $f_o$ from a source with intrinsic (emitted) luminosity, $L_e$, the luminosity distance, $d_L$, is defined by:

$$f_o = \frac{L_e}{4\pi d_L^2}$$

Luminosity distance takes into account distance, redshift, and geometric effects. Angular diameter distance, $d_A = d_L(1+z)^2$, is the size of an object on the sky.